LOCTITE®

ADHESIVE
TECHNOLOGIES
EXPERT BONDING
COLLECTION

HOW TO CREATE RELIABLE **AND EFFECTIVE BONDED JOINTS**

Contents

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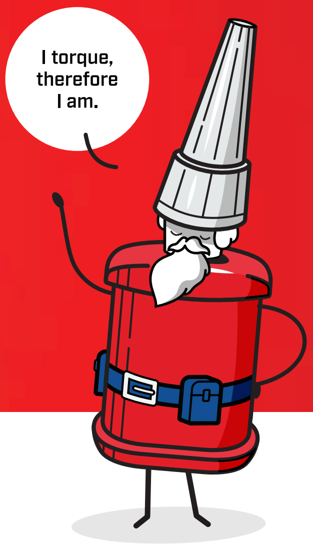

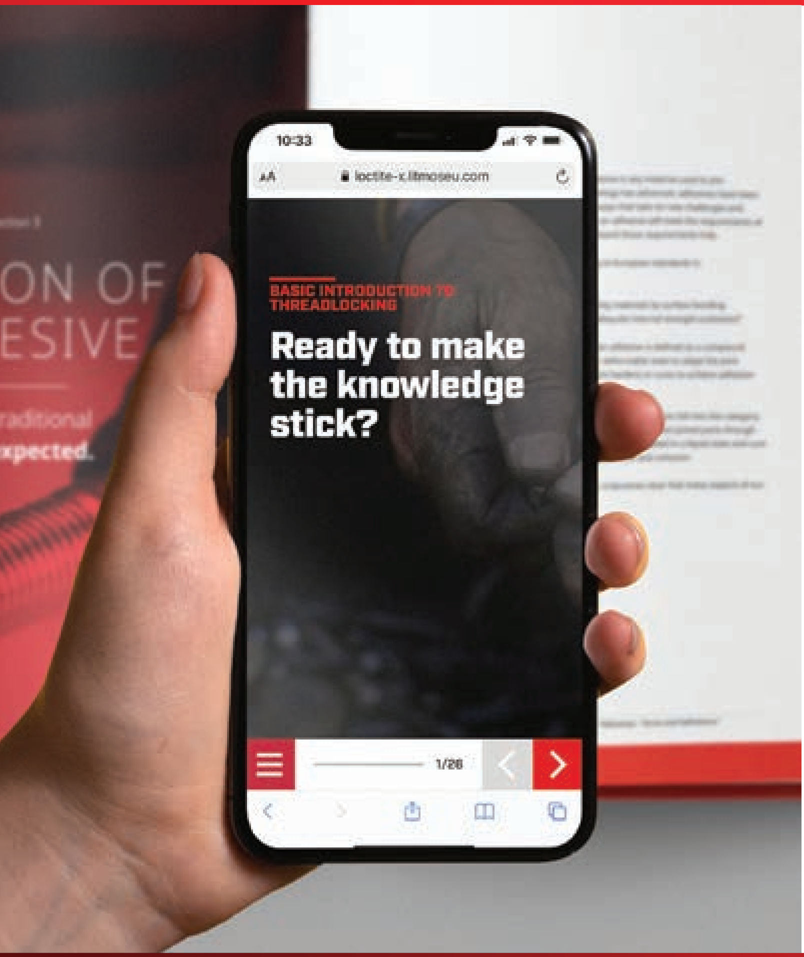

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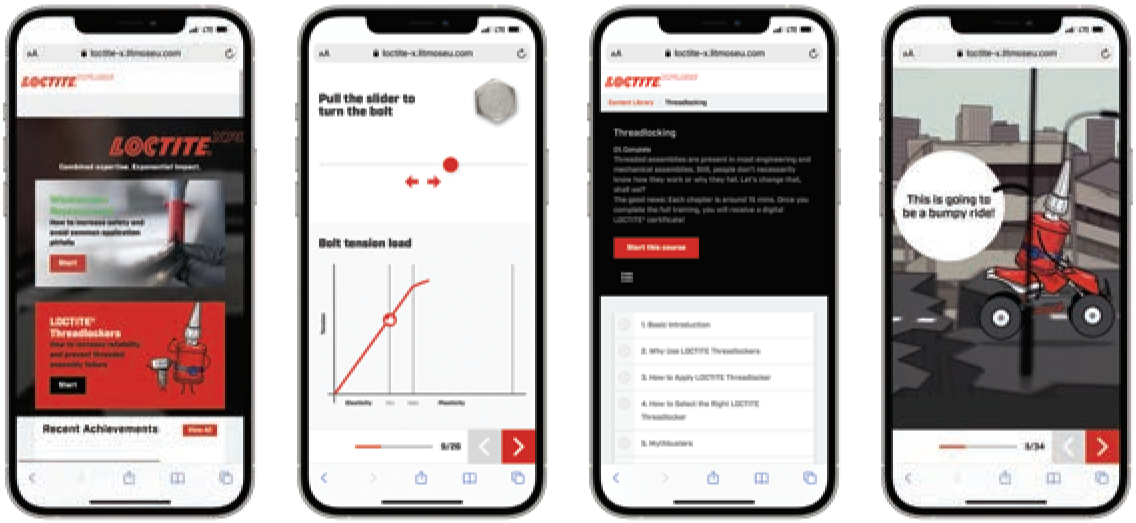

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FOREWORD

IN 1876, FRITZ HENKEL'S PIONEERING SPIRIT LED HIM TO RECOGNISE THE NEED FOR A UNIVERSAL DETERGENT BASED ON SILICATE. From that day forward, Henkel's focus on solving technical challenges has helped us build a vast body of expertise as a global manufacturer of adhesives, specialty coatings, laundry products and beauty care products.

LOCTITE®, one of Henkel's flagship brands, reflects and drives much of that expertise. As the global leader in bonding, sealing and specialty coatings, our passion for solutions that unlock the limitless potential of man and machine allows us to provide the support you need to solve your design, engineering, assembly and maintenance challenges. Our global leadership position in the adhesives market could not have been achieved without the expertise, dedication and knowledge of LOCTITE® and our technical teams across the globe. It is our intention that this expert series will be used as a reference text that enables you to unleash the potential of adhesive technologies beyond the obvious.

By driving innovation and working collaboratively with customers, channel partners, industry leaders and academia, we have helped enable our partners to achieve technological breakthroughs beyond their expectations. Our mission is to create substantial new value for our customers and facilitate sustainable growth. Many customers have commented on the expertise of the LOCTITE® teams with which they interact. The compliment is well-earned, as our people include many leading patent holders and members of certification bodies. They are some of the finest minds in industry, and their deep knowledge of current technologies, combined with their focus on the future, will be a great support to you in the development of new applications.

Now, just as our innovation and partners have enabled us to build our expertise, we want to empower you. While the expertise of our technical teams is a source of great pride to us, our greater goal is to help you solve your technical challenges by providing insight into adhesive technologies. This module, part of the 'Adhesive Technologies Expert Bonding Collection' on bonding, sealing and specialty coating applications, is part of that effort.

We are proud to share our expertise with you in this module, our face-to-face and virtual interactions, and in digital books and e-learnings within our LoctiteX digital content platform. We hope the knowledge we've assembled here will help make your products and assemblies more powerful, sustainable, durable and efficient and will have a positive impact on your business beyond your expectations!

With pride and gratitude,

Dr. Nigel Fay

Corporate Vice President
Innovation & Application Engineering
Henkel Adhesives Technologies

Nigel Fay

Dr. Kourosh Bahrami

Senior Vice President
Henkel Adhesives Technologies

INTRODUCTION

THANK YOU FOR TAKING AN INTEREST IN UNDERSTANDING ADHESIVES AND BONDING. Adhesives have allowed for great technological leaps forward (e.g. touchscreens and LCDs), and today, they can be found in just about every application. They are stronger and more reliable than ever before, and they've made numerous products safer, lighter and more reliable. The content you'll find here explores the basics of adhesives, bonded assemblies, and how to engineer with them reliably.

Our goal with this book is to help you make informed decisions that improve the efficacy of bonded joints within assemblies and open up more design possibilities. By making our technical and scientific knowledge of adhesives available, we hope to help you overcome design challenges, increase the reliability of bonded joints and product life, and reduce costs. Ultimately, our hope is that you will use this expertise to overcome a wide range of design and engineering challenges.

This book is the culmination of our 65+ years as a leading manufacturer of adhesives and features the expert knowledge of more than 40 contributors. This book would not have been possible without their efforts. As we have developed and manufactured adhesive technology and built expert engineering and product development teams, we have learned how to help shape advancements in manufacturing and maintenance processes and seen how adhesives can unlock limitless potential.

Ambra Chierico

Application Engineering Manager, Italy, Greece, Spain and Portugal

16 years at Henkel

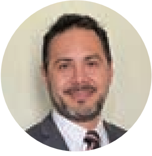
Current Location: Casarile, Italy

Product Technology Expertise: Polyurethanes, Silane Modified Polymers (SMP), Hotmelts

Ambra joined Henkel after attaining a degree in chemistry from the University of Pavia in Italy.

She started her career in technical customer service, visiting customer manufacturing sites and conducting lab testing to help qualify customer applications. She has worked on many applications for leading international manufacturers, helping to validate adhesive applications in recreational vehicles, filters and household appliances.

During her 16 years with Henkel, she has focused on flexible adhesives (SMP, Silicones), polyurethanes and hotmelts, becoming an expert in these chemistries and technologies. She now leads Henkel's Technical Customer Service department for Italy, Spain, Portugal and Greece, helping to develop the next generation of adhesive engineers.



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Director of Application Engineering General Manufacturing and Maintenance

21 years at Henkel

Current Location: Rocky Hill, CT, USA

Product Technology Expertise: Anaerobic Machinery Adhesives, Cyanoacrylates, Structural Adhesives, Silicones, Silane Modified Polymers (SMP), Polyurethane (PU)

Gustavo joined Henkel in Mexico in 2000 as part of the Engineering Adhesives team. He later became a key account manager in Henkel's automotive business in Latin America between 2011 and 2012. During this time, he gained experience managing large consumer automotive, commercial truck and bus customers. After a period in Spain as the technical customer service manager for OEM business, Gustavo moved to Henkel's US headquarters in Rocky Hill, CT, USA, where he has held a number of management roles for vehicle repair and maintenance (VRM) and global technology management. Most recently, in 2020, he took on the role of US technical customer service director for general manufacturing and maintenance.

Throughout his career, Gustavo has been characterised by his dedication to strengthening and developing the knowledge of customer service, sales technicians and the customers with whom he interacts.

Michael Konhäusner

Head of Application Engineering, Eastern European South

31 years at Henkel

Current Location: Vienna, Austria

Product Technology Expertise: Adhesives Generalist, Substrates Expert

Michael started his career at Henkel in 1990 as a sales engineer, helping a wide variety of customers to achieve their design goals through the use of adhesives. Throughout his career in Henkel's adhesives businesses, he has held various management positions in customer service, sales and marketing, and today he serves as Loctite's technical customer service manager for Eastern Europe South, where he has been able to fully apply his educational background as a plastics engineer.

Michael has been essential to the success of global training programmes and has helped shape and launch global digitalisation projects.

Rudolf Neumayer

Sales Excellence and Training Technical Lead

33 years at Henkel

Current Location: Munich, Germany

Product Technology Expertise: Anaerobic Machinery Adhesives, Cyanoacrylates, Structural Adhesives

Over Rudolf's 32 years with Henkel, he has become one of our leading technical experts in Europe, supporting both manufacturing and maintenance operations. He has helped troubleshoot and specify threadlocking applications across a broad range of industries, including heavy duty equipment, powered drive systems, automotive powertrains and general industrial manufacturing. Rudolf holds an engineering degree in plastics technology.

Lucas Hyunseob Shim

Senior Application Engineer

8 years at Henkel

Current Location: Seoul, Korea

Product Technology Expertise: Anaerobic Adhesives, Structural Adhesives, Light Cure Adhesives

Lucas joined Henkel in 2013 as an intern but moved into Application Engineering in 2014. He has an exceptionally strong background in processes currently employed in industrial manufacturing. During his time at Henkel, he has helped customers overcome unique design challenges using adhesives and facilitated innovation in manufactured goods. His experience covers many industries, including electric motors, household appliances, power transformers, LNG and shipbuilding.

Lucas takes great pride in helping end users leverage the knowledge Henkel can offer to build total solutions and bring cutting-edge designs to life.

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SECTION ONE

INTRODUCTION TO JOINING

HUMANS HAVE BENEFITED FROM JOINING MATERIALS FOR THOUSANDS OF YEARS. The technological leaps made to create tools and structures gave early humans an important survival advantage by saving time and energy and increasing productivity and efficiency. From the earliest example of joining stone and organic materials, such as those illustrated in Figure 1, to today's high-tech adhesives, humans have continually advanced the art and science of joining materials with a variety of techniques.

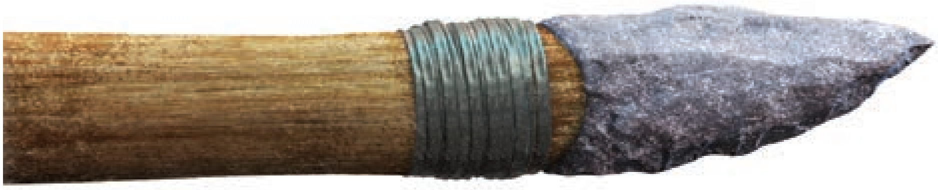


FIGURE 1

A primitive weapon made by bonding two different materials (wood and stone) using a primitive adhesive and mechanical reinforcement with a string of natural material

Archaeologists found the first evidence of adhesives in a 70,000-year-old burial site where broken pottery vessels had been repaired with sticky tree resins. Babylonians used a tar-like adhesive almost 6,000 years ago to glue ivory eyes into statues. Paintings and murals from around 1500 to 1000 B.C. depict the details of craftsmen gluing wood. Many cultures throughout the centuries employed glues made from animal hide, bones, milk, beeswax and grains in furniture, veneering and marquetry, and ship and weapon building. The treasures of the Egyptian pharaohs, including those discovered in the tomb of King Tutankhamen, were joined with animal-based adhesives.

By 1700, the use of glue was widespread, and technology saw rapid changes. The first commercial glue factory manufactured animal hide glue in Holland. Around 1750, the first glue patent was issued in Britain for fish glue. Patents quickly followed for adhesives using natural rubber (NR), animal bones, fish, starch and milk protein (casein).

The Industrial Revolution in the 18th to 19th centuries saw an explosion in technical breakthroughs in adhesive formulation. The first plastic polymer, cellulose nitrate, was synthesised from wood cellulose. Its first use was to replace ivory in the manufacture of billiard balls.

The plastic era dawned in 1910 with the introduction of Bakelite phenolic, a thermoset plastic. It was quickly followed by phenolic resin adhesives. The 1920s to 1940s were a time of rapid development of new synthetic plastics and rubbers, many of which played essential roles during World War II.

FIGURE 2

Emergence of important joining methods over the course of human history

70,000 BC – First evidence of tree pitch used as an **adhesive**

3000-4000 BC – Evidence of **soldering** and **brazing**

3400 BC – Egyptians invent **nails** (Bronze)

3200-600 BC – Evidence of the invention of **rivets** (Bronze)

2000 BC – Egyptians use liquid adhesives in wooden artifacts (animal glue)

400 BC – Archimedes develops the **'screw principle'**

1700 – First commercial glue factory opens in Holland **(animal glue)**

1770 – Invention of a lathe capable of cutting threads on a fastener. **'Invention' of the bolt**

1845 – **Pressure Sensitive Adhesive (Tape)** invented

1881 – August De Meritens invents **welding** (Electical Arc)

1920s – **Synthetic adhesives** first commercial production

1934 – **Epoxy adhesives** patented in Germany

1935 – Howard Hughes invents the **flush rivet**

1950s – **Polyurethane adhesives** widely adopted

1991 – **Friction stir welding** invented and proven in the UK

Today, adhesives made from animal by-products have been almost entirely supplanted by synthetic formulations. The development of adhesives alongside plastics and elastomers has enabled formulators to manipulate adhesive properties such as flexibility, toughness, curing or setting time, temperature and chemical resistance.

These new adhesives are so versatile and prevalent in our society that they are nearly invisible. If you are reading this on a screen or in a printed book, are sitting on furniture, in a car or on an aeroplane and are wearing shoes, jewellery or a smart watch, then you are surrounded by things held together, coated, protected or enhanced in some way by adhesives.

Today, adhesives hold our world together. The next section summarises some other common methods of joining materials.

1.1 CONVENTIONAL METHODS FOR JOINING

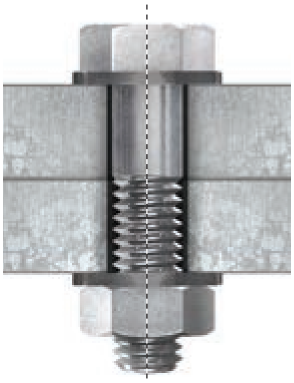
Joining materials are mechanical, thermal and chemical. Mechanical joining relies on devices such as bolts and rivets, or on the distortion of the material itself, such as folding, press-fitting or shrink-fitting, to secure the components of an assembly. Thermal joining methods for metals include welding, brazing and soldering. There are several thermal methods of plastic welding. Chemical joining methods include adhesive and, for plastics, solvent bonding. Every technique has pros and cons: operation conditions, expense, geometric tolerances and disassembly requirements are just some of the considerations when joining materials together.

1.1.1 MECHANICAL JOINT: THREADED FASTENERS

Threaded fasteners are the ideal method of mechanically joining elements when occasional and easy disassembly of the joined parts is required. Threaded fasteners require the expense of drilling and tapping the parts to be joined, often to specified tolerances. The fastener sites concentrate stress, which, if severe enough, may require the parts to be reinforced at those points. Threaded fasteners can provide a very strong clamping force but may fail over time due to vibration and cyclic loading, and corrosion is a concern in humid, marine or chemical environments. Adding a chemical bonding agent – an adhesive – to a threaded fastener can reduce or eliminate many of these issues. For an in-depth discussion of threadlocker adhesives and threaded assemblies in general, refer to the manual in this series titled *How to Increase Reliability and Prevent Threaded Assembly Failure.*

FIGURE 3

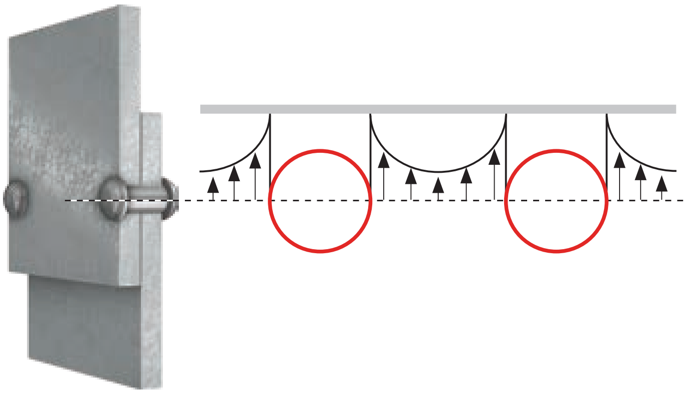
Threaded fastener joining two plates



F3

FIGURE 4

Stress risers occur at threaded fastener or rivet locations



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1.1.2 MECHANICAL JOINT: RIVETS

Rivets are cylindrical shanks with a head at one end used to permanently join two plates. Like threaded fasteners, they require holes to be drilled into the materials being assembled. After insertion through the holes, the end of the rivet shaft opposite the head is flattened and deformed so that it cannot be removed, securing the parts together. Because it cannot be disassembled without destroying the rivet, it is considered a permanent joint. Like threaded fasteners, rivets may cause stress concentrations that require components to be reinforced at these locations, adding to the weight and machining requirements. Also, like threaded fasteners, rivets do not seal leak paths and are vulnerable to corrosion.

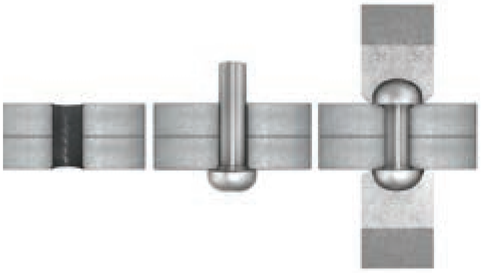


FIGURE 5

Rivet joint

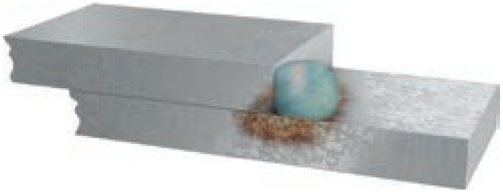


FIGURE 6

A mechanically joined assembly; lack of sealing capability leaves assemblies vulnerable to moisture ingress and subsequently corrosion

1.1.3 MECHANICAL JOINT: KEYWAY

Keyways transmit torque between a shaft and gear by means of a rectangular key secured to the shaft by dowels, pins or set screws. Machining costs for tolerances required by keyways may be significant. The diameter of a shaft in which a key is seated must be increased by up to 30% to accommodate the key while supporting the torque load.

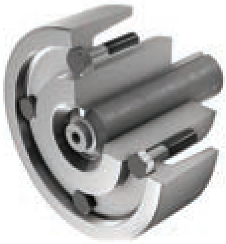


FIGURE 7

Shaped joints with intermediate elements as a key

FIGURE 8

Fastening methods for cylindrical joints between shaft and element on shaft (gear, pulley) mounted using a keyway and set-screw

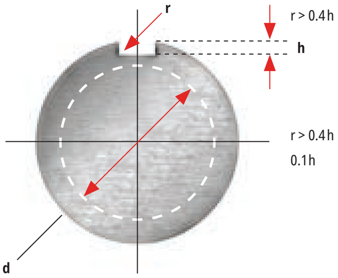


FIGURE 9

Shaft diameter must be increased to accommodate a key

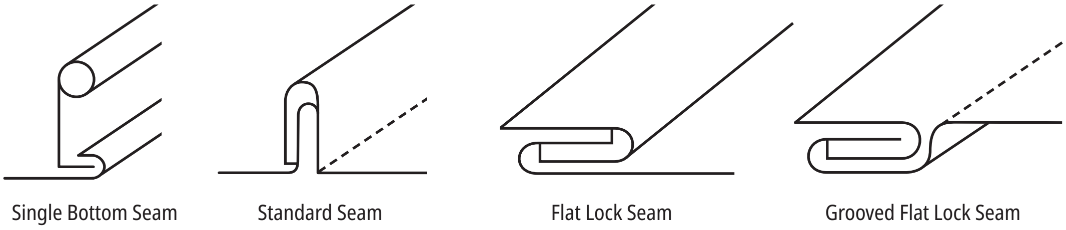
1.1.4 MECHANICAL JOINT: FOLDING OR CLINCHING

Two pieces of sheet metal can be connected to each other by folding or bending tabs in the form of a buckle and a clamping slot in a folded joint. This assembly method is relatively quick, reliable, economical and convenient.

However, folded metal joints do not seal and may be susceptible to corrosion. These types of joints require a relatively long contact area to provide strength and are not suitable for plastics.

FIGURE 10

Examples of mechanically folded joints



1.1.5 MECHANICAL JOINT: PRESS FIT

Press fits, or interference fits, involve an inner component, such as a shaft, forced into an undersized hole. Once assembled, the parts are held together by the friction of the press fit. Press fits require machining to tight tolerances and precise, accurate placement at high force, typically with a hydraulic press.

1.1.6 MECHANICAL JOINT: SHRINK FIT

A shrink-fit joint is an extreme form of an interference fit. The negative clearance is larger than that of a standard press fit, with the outer diameter of the inner element being significantly larger than the inner diameter of the component or sleeve into which it is pressed. To achieve this assembly, the outer sleeve is heated before the inner component is forced into it. Because the outer element will cool very rapidly and the inner element will heat up, the assembly must be completed quickly as it will not be adjustable once it has cooled. In addition, the outer component will be under high stress and may be designed to be larger and heavier to compensate.

Press-fit joints and shrink-fit joints can cause high stresses that lead to the destruction of the assembly (Figure 12), especially during the operating time when the hub has a load caused by a torsional moment.

FIGURE 11

Press fit tolerances are designed with negative clearance while still allowing room-temperature assembly

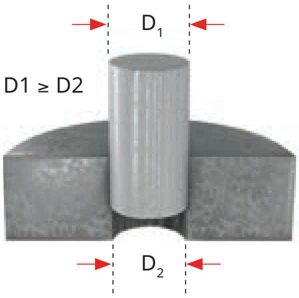
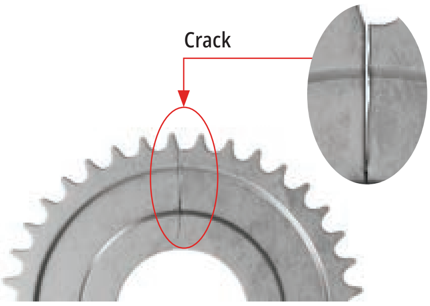


FIGURE 12

Excessive press fit or shrink fit stress may contribute to failure during assembly or disassembly, or even during operation, if combined stresses are too high

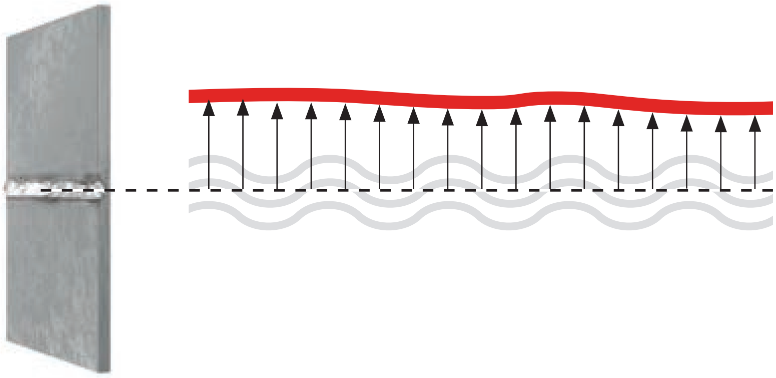


1.1.7 THERMAL JOINT: WELDING

Welding is used to join similar metals. Welding produces a very strong joint and is generally suited to large assemblies where both metal sections are relatively thick (>=12.7mm (0.5 in)). Welding creates a localised joint and is not suitable for broad areas. Welded joints are considered permanent as disassembly is impractical or impossible. Because the base material is melted, the part may undergo deformation, internal stresses and undesirable cosmetic effects. The ductility and toughness of the base material may be locally affected. Welding requires skilled labour and knowledge of basic physics, chemistry and metallurgy principles. Highly flammable gases and/or specialised equipment are also required. Welding is not suitable for small items.

FIGURE 13

A weld can create large internal stresses, leading to deformation of the material

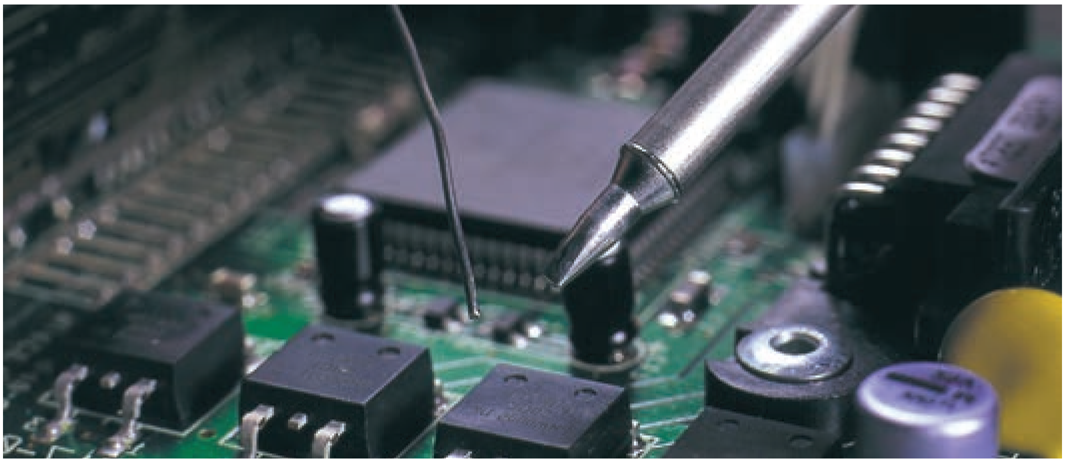


1.1.8 THERMAL JOINT: SOLDERING

Soldering joins metal parts with a molten filler metal rather than melting the base material of the part. Solder is typically a tin or lead alloy that melts at temperatures below 350°C (662°F), causing less thermal stress than welding. Melted solder is drawn by capillary action between metal surfaces. It is electrically conductive, suitable for small parts and may be reworked at relatively low temperatures, which makes it a popular choice for electronics.

FIGURE 14

Soldering and joining metal contacts in electronics



1.1.9 THERMAL JOINT: BRAZING

Like soldering, brazing does not melt the base metals. Brazing temperatures are higher than soldering, ranging from 450°C (840°F) to 800°C (1,470°F) for hard brazing. Brazing creates a metallurgical bond between the filler metal and the surfaces of the two metals being joined. Heat is applied broadly to the base metals; when the filler metal is brought into contact, it is melted and drawn by capillary action through the joint.

The most significant advantage of brazing over welding is that the base metals are not melted, so they can retain most of their physical properties. Base metal integrity is a characteristic of all brazed joints, including thin- and thick-section joints. The lower heat also minimises the danger of metal distortion or warping.

Brazing offers a significant advantage in joining dissimilar metals, including copper and steel, as well as non-metals, such as tungsten carbide, graphite and diamond. A properly brazed joint, in many cases, could be as strong or stronger than the metals themselves.

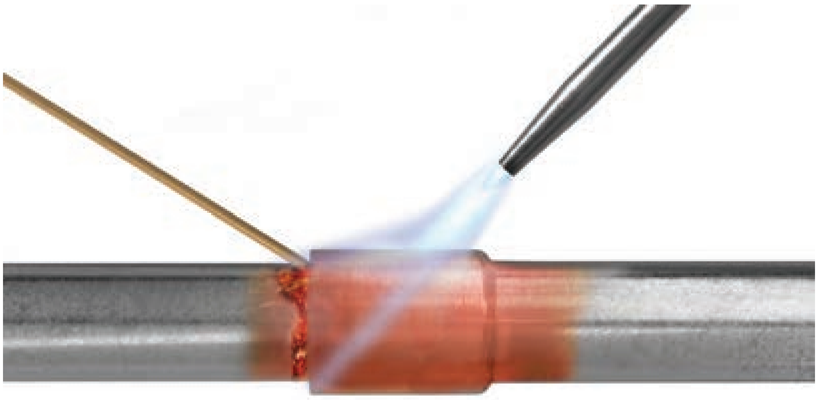


FIGURE 15

Brazing produces a strong joint and seals against internal pressure

1.1.10 THERMAL JOINT: ULTRASONIC WELDING

Ultrasonic welding melts the contact surfaces of two substrates by ultrasonic vibration causing friction and, in turn, producing heat. The thermal energy comes from the reciprocating movement of a substrate on another surface. When heated this way under pressure, substrates form a close bond once cooled.

Ultrasonic welding of plastics is popular for its speed, safety and small environmental footprint in industries such as medical, power, automotive and toy manufacture.

The technical requirements of ultrasonic welding of metals are higher than those of plastic. Large metal parts create complex problems for ultrasonic welding, so the most common applications are for small parts such as wire harnesses, terminal connections, and batteries.

Ultrasonically welded metals have the advantages of lower resistivity, electrical conductivity, and high joint strength. The welding process does not require or produce weld spatter, bright light, flux or protective gas, resulting in improved safety and environmental protection.

1.1.11 THERMAL JOINT: THERMAL PLASTIC WELDING

Thermal welding merges thermoplastic parts with heat and pressure. Many plastics can be welded, such as acrylic or polymethyl methacrylate (PMMA), polycarbonate (PC), polyethylene (PE), polypropylene (PP), polyethylene terephthalate (PETE or PET), polyvinyl chloride (PVC) and acrylonitrile-butadiene-styrene (ABS). Plastic welding may also repair cracks in damaged plastic pieces.

Requirements include hot air welding tools, plastic welding rods, extruders, heating and cooling time, and pressure. Most plastic welding processes require fixtures to hold the plastic components together to form a complete bond as the heat is added to the weld joint.

1.1.12 CHEMICAL JOINT: SOLVENT WELDING

Solvent welding uses a solvent to dissolve the surfaces of two chemically similar plastic parts. When the two parts are pressed together and the solvent evaporates, the surfaces are permanently fused. Solvent welding is used for plastics like PVC and ABS, which may be dissolved by solvents. The solvent must be chosen for the specific plastic being welded. Plastics that are not vulnerable to solvents, such as PP and PE, cannot be solvent welded. Manufacturers with concerns about solvents may avoid using this technique.

1.1.13 CHEMICAL JOINT: ADHESIVES

The term **adhesive** covers a large and varied group of materials with an enormous range of properties and potential applications. There are so many types of adhesives available that the task of selecting one can be bewildering. While an undemanding application may do well with any number of bonding agents, other applications require special characteristics only found in a selective few adhesives. Understanding the requirements of the application will go a long way towards zeroing in on a good adhesive choice. We'll start by discussing some basic classifications of adhesives.

1.1.13.1 BASIC CLASSIFICATION

The broadest classification scheme categorises an adhesive as organic or synthetic. This manual focuses on synthetic adhesives, which are the most commonly used adhesives today by far. Modern adhesives systems that are used in demanding structural applications are made from synthetic polymers.

Adhesives may be classified by chemistry, common uses, means of turning from a liquid to a solid (which not all adhesives do), ease of use, method of application, speed of cure – in fact, there are so many characteristics that a diagram of these classifications would be a complex tangle of overlaps and contradictions. For the purposes of this text, we focus on function, chemical composition and type of reaction.

1.1.13.2 FUNCTION

One source suggests dividing adhesives into structural and non-structural classes, depending specifically on their ability to produce shear strength above 6.9 N/mm^2 (1,000 psi).(1) While the figure is somewhat arbitrary, the concept is sound: a structural joint (or bond) is expected to be load-bearing, strong, rigid, durable and able to last for the life of the assembly. Examples of non-structural applications include the attachment of lightweight, non-load-bearing components, coating, potting and gasketing.

While adhesive types like epoxies and acrylics are generally considered structural bonders, the conditions of the application – substrate, environment, geometry, etc. – will strongly influence the strength and durability of the joint. Likewise, in the right conditions, adhesives not normally considered 'structural' (silicones, threadlockers and even pressure-sensitive tape) may create a structural bond. The context and conditions of the application are key considerations.

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1) Petrie, Digital Engineering Library; digitalengineeringlibrary.com, 280-281, McGraw-Hill, 2000.

1.1.13.2.1 CHEMICAL COMPOSITION

Adhesives may also be classified by chemical composition as thermosetting, thermoplastic and elastomeric varieties.

1.1.13.2.2 THERMOSETTING ADHESIVES

Epoxy, urethane and acrylate adhesives are common examples of thermosetting adhesives. Thermosetting adhesives cure by an irreversible chemical reaction, referred to as crosslinking, which is brought about by the linking of two linear polymers, resulting in a rigid three-dimensional chemical structure. Some crosslinked reactions require heat for initiation and completion, while others can be completed at room temperature. With certain 'room temperature' curing adhesives, it is the internal heat of the reaction generated by the curing mechanism, called the exotherm, which provides the energy required to completely cure the polymeric material.

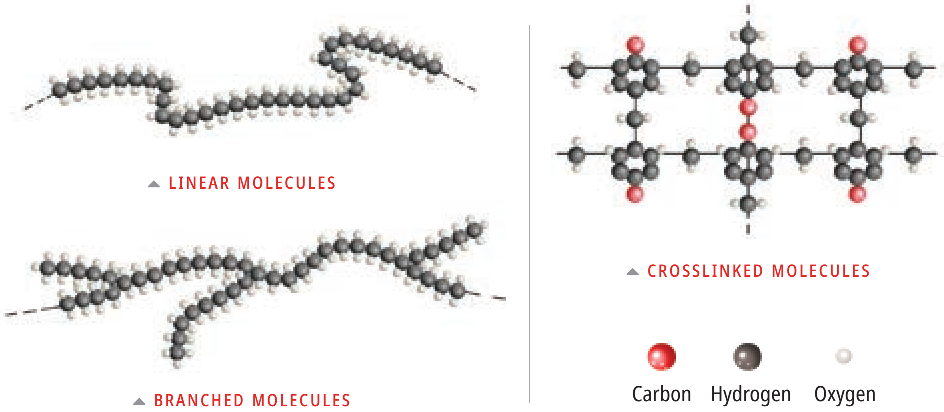
Thermosetting adhesives (like thermosetting plastics), once cured and crosslinked, cannot be reheated, melted or reused. This thermosetting property gives them good heat resistance compared to thermoplastic varieties, which may be remelted. High enough heat may soften and degrade thermosetting adhesives through oxidation or molecular chain growth polymerisation.

Thermosetting adhesives may be one-component (1C) or two-component (2C) systems. A 2C system, such as the resin and hardener of epoxy, is stored separately and mixed at a specified ratio (weight or volume) just before use to initiate the chemical reaction and crosslinking. Mixing may be done by hand, in dual cartridges with static mixer tips or in large industrial equipment designed for the purpose. Care should be taken to observe the manufacturer's stated 'open time' as the best bond to the substrate will occur before crosslinking thickens and begins to harden the adhesive. A 2C adhesive system generally offers a longer shelf life because the reactive components are separated from each other until mixed for use.

Crosslinking endows thermosetting resins with high strength, rigidity and superior resistance to heat and solvents, making them a frequent choice for structural joints.

FIGURE 16

Chemical reaction known as crosslinking. The result is a three-dimensional rigidised chemical structure. Here are some possible molecular structures in polymeric resins used as adhesives



▲ LINEAR MOLECULES

▲ BRANCHED MOLECULES

▲ CROSSLINKED MOLECULES

1.1.13.2.3 THERMOPLASTIC ADHESIVES

Thermoplastic adhesives are not crosslinked and, unlike thermosetting adhesives, can be remelted and reused. Generally speaking, they are usually sold in solid form, melted in a dispenser and applied as a liquid to the surface to be bonded. When the thermoplastic adhesive cools, the bond is secured. 'Hotmelt' a.k.a. 'hot glue' is a well-known type of thermoplastic adhesive.

Reusability of these adhesives is limited; thermal ageing and degradation will occur from oxidation and repeated exposure to the high temperatures required to melt these adhesives.

Another common use of thermoplastic as an adhesive is to dissolve it in a solvent to produce a flowable solution which is then applied and hardened when the solvent evaporates. Thermoplastic resins can also be dispersed in water and applied as latex or emulsion. Common household wood glues are examples of this.

Thermoplastic adhesives can also be pre-applied to a substrate for later use in either heat or solvent activated form. The gummed flaps on mailing envelopes are a well-known example of a solvent-activated adhesive; it is moistened to activate it and secure once dry.

Owing to the lack of crosslinking, thermoplastic adhesives have a limited service temperature range compared to that of thermosetting adhesives. While some thermoplastics provide excellent tensile shear strength at room temperature, others can creep at room or even lower temperatures, which limits their use for structural joints. Users should investigate the creep properties of a thermoplastic adhesive before specifying it in a structural bond, especially where elevated temperatures are anticipated. Thermoplastics are also less resistant to the effects of solvents and chemicals, which is also due to the lack of crosslinking in their molecular structure.

1.1.13.2.4 ELASTOMERIC ADHESIVES

Elastomeric adhesives possess unique rheological characteristics and have their own classification. The synthetic or naturally occurring elastomeric polymers on which they are based allow them to withstand considerable compression or elongation before suffering plastic (permanent) deformation. While materials, when unloaded, will return to their original dimensions if they have not been deformed beyond their yield point, elastomeric polymers and adhesives can be deformed considerably – sometimes several times their initial length – before this point is reached. Compare this to a rigid epoxy's single-digit percent elongation before yield. Elastomeric adhesives excel in energy absorption and are commonly used for sealing, vibration damping and soundproofing. Their flexibility and low modulus make them robust in joint designs requiring resistance to peel and cleavage forces, non-uniform loading, flexure and thermal expansion differentials.

The same low modulus and high elongation that makes them so valuable in situations requiring flexibility render elastomeric adhesives less desirable for structural bonding, which requires high rigidity and load-bearing properties. Crosslinked thermosetting elastomeric adhesives may be considered for structural joints, but these applications must be carefully vetted for the reasons outlined above.

Elastomeric adhesives may be supplied as solvent-based solutions, water dispersions, pressure-sensitive tapes and single- or multiple-part solventless liquids or pastes. The form and curing requirements vary according to the type of elastomeric resin used in the adhesive formulation.

1.1.13.2.5 TYPE OF REACTION

Adhesive cure mechanisms are many and varied and must be considered when designing a bonded joint. Some adhesives solidify simply by solvent evaporation, cooling from liquid to a solid, or a chemical reaction initiated by the mixing of components. An external energy source like heat, or an initiator such as moisture in the air, may be required for curing. Some systems have multiple cure mechanisms, such as activator-cured acrylic that may also be cured by heat. Others may require a dual cure, as in a light cure silicone that is fixtured by UV radiation but reaches its final form and properties via subsequent moisture curing.

The curing method will be a factor in adhesive choice. The cost or space requirements of specialised dispensing or curing equipment may also be a decision point, as will any health and safety concerns for the chemicals or energies required by a given adhesive system. Process speed will vary enormously by curing mechanism – a light cure acrylic may cure in seconds, while Room Temperature Vulcanizing (RTV) silicones may take hours to reach handling strength and days to fully cure. These factors must be balanced with the design requirements of the product, as cure mechanisms favour certain properties. For example, heat cured adhesive systems generally offer better thermal resistance from the additional crosslinking that occurs with a higher temperature cure. Light cure adhesives cure on demand but tend to display increased shrinkage compared to other technologies.

The following hierarchy groups adhesive families by method of reaction:

1. Adhesives that harden by chemical reaction
    a. 2C systems
    b. 1C systems, cured via catalyst or hardener
    c. Moisture-curing adhesives
    d. Radiation (light, UV, electron beam, etc.) curing adhesives
    e. Adhesives catalysed by the substrate
    f. Adhesives in solid form (tape, film, powder, etc.)

2. Adhesives that harden by solvent or water loss
    a. Contact adhesives
    b. Pressure-sensitive adhesives
    c. Reactivatable adhesives

3. Adhesives that harden by cooling from a molten state
    a. Hotmelt adhesives
    b. Hotmelt applied pressure sensitive and thermosetting adhesives.

SECTION TWO

THE BASICS OF JOINING

PRIOR TO SELECTING A PARTICULAR JOINING METHOD, MANY FACTORS NEED TO BE UNDERSTOOD TO CREATE THE MOST RELIABLE AND EFFECTIVE ASSEMBLY. As each assembly is different, the goal of this section is to establish an understanding of the processes used to identify appropriate substrates and to define important characteristics that impact joining method selection. Factors such as specific assembly strength requirements, testing requirements, applied forces and loading conditions, the permanence and required durability of an assembly, manufacturing and design parameters, and substrate characteristics need to be considered before selecting a joining method. It is also important to quantify these factors to ensure that the final assembly meets and, where possible, exceeds the minimum performance expectations. This section covers these topics in depth.

2.1 INTRODUCTION

Companies are under increasing pressure to meet consumers' expectations for high quality products while operating more efficiently with less downtime. One of the major goals in manufacturing processes is to maximise overall equipment effectiveness (OEE), to reduce and/or eliminate what are known as the 'Six Big Losses'(2) – the most common causes of equipment-based productivity loss in manufacturing.

TABLE 1

The Six Big Losses

OVERALL EQUIPMENT EFFECTIVENESS	UPDATED	TRADITIONAL
Availability Loss	▸ Unplanned Stops ▸ Planned Stops	▸ Equipment Failure ▸ Setup and Adjustments
Performance Loss	▸ Small Stops ▸ Slow Cycles	▸ Idling and Minor Stops ▸ Reduced Speed
Quality Loss	▸ Production Rejects ▸ Startup Rejects	▸ Process Defects ▸ Reduced Yield
OEE	**Fully Productive Time**	**Valuable Operating Time**

This OEE assessment involves not only equipment maintenance but all aspects of machine operation, installation and production. This approach can also be applied to operators and production staff. OEE measurement is based on the top three categories of six big losses: availability rate/loss, performance rate/loss and quality rate/loss. Although it is difficult to achieve zero loss, it is believed that striving for zero defects is an important prerequisite for the success of the total productive maintenance (TPM). Table 2 defines the ideal OEE values.

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2) *Six Big Losses*, https://www.oee.com/oee-six-big-losses.html#equipment-failure.

TABLE 2

Ideal Value of OEE[3]

90%	95%	99%	85%
Availability	Performance	Quality	OEE

To achieve these optimum values, where 100% equates to perfect production, the process of product development must be meticulously considered. Section 2.2 describes the factors that can affect assembly quality. OEE should achieve a value of >85% by effectively reducing the impact of the six big losses. With OEE scores in this range, production will run as efficiently as possible. The quality of a finished product should be directly proportional to the manufacturing process; a higher OEE score translates to an improved final assembly. Constant quality control throughout the entire production cycle is necessary to deliver the highest quality product. Testing is one of the most efficient and valuable quality control tools used by manufacturers. Many joining methods can be used to maximise the effectiveness of a piece of equipment, assembly or joint; however, proving the effectiveness is critical.

2.1.1 TESTING REQUIREMENTS

It is of critical importance that assemblies and joined components undergo thorough testing and validation. Testing and assessing the materials, joining methods, and finished parts are key to validating a design. It is also essential to ensure that the finished product is fit for its purpose and can operate and perform to the necessary levels outlined during the conception, design and prototyping phases. The testing of actual parts should be mandatory, but consideration should also be given to the method of production/assembly and the varying results different approaches and processes may yield.

2.2 FACTORS FOR JOINING METHOD

2.2.1 SUBSTRATES

Many substrates are used in the manufacturing industry. The following sections present some characteristics of the most common substrates.

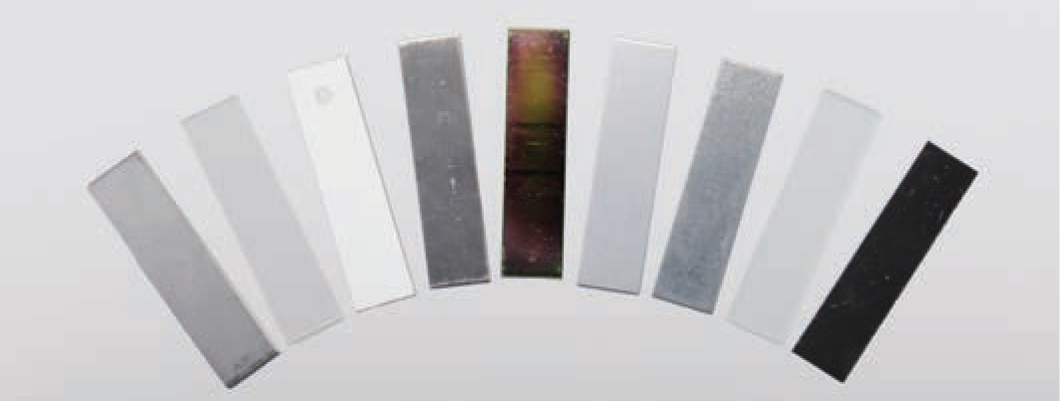


FIGURE 17

A variety of substrates that may be used in joining applications

2.2.1.1 METAL

A multitude of different metals and their alloys are used to realise every conceivable application. Two of the most commonly used metals are aluminium and steel. For more detailed information regarding metals, see the *Loctite® Design Guide for Bonding Metals.*

2.2.1.1.1 ALUMINIUM AND ANODISED ALUMINIUM

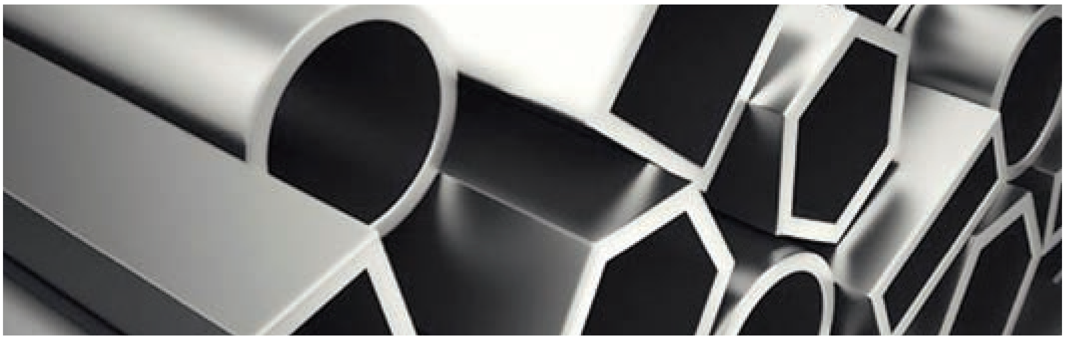


FIGURE 18

Examples of aluminium semi-finished products

Aluminium and its alloys are the most widely used nonferrous metals because they offer the benefits of corrosion resistance, versatile and desirable aesthetics, ease of fabrication, low density, and high electrical and thermal conductivity. Limitations of these metals include low fatigue and wear resistance, a low melting point and lower modulus of elasticity compared to most ferrous alloys. However, aluminium and its alloys generally have good corrosion resistance due to a reaction with oxygen that forms a hard, microscopic aluminium oxide layer inhibiting a reaction between corrosive elements and the base aluminium alloy. Whilst this oxide layer offers benefits such as corrosion resistance, it can reduce the surface adhesion of the aluminium or aluminium alloy and, without appropriate preparation, adversely affect subsequent processes such as adhesive bonding, painting and coating.

Anodising processes build up the oxide layer, formed through a reaction with oxygen, to create a thicker, protective coating which is tightly bound to the base aluminium alloy. The resulting aluminium oxide layer can offer electrical insulation, protection from corrosion, improved abrasion resistance, a lasting decorative finish and a stable surface for bonding, coating or other secondary operations.

TYPICAL APPLICATIONS OF ALUMINUM	
Construction	windows, facades, doors, conservatories, sunshades, shower cubicles, railings, roof and wall systems, lightning conductor constructions, photovoltaic systems supporting structures
Aerospace	aircraft structures, mechanical components
Automotive	vehicle bodies, chassis, engine blocks, gearboxes, tailgates, doors, rims, cylinder heads, wheels
Railway	superstructures, vehicle bodies, infrastructure, rolling stock components
Industrial	cylinders (hydraulics, pneumatics), overhead cables
Electronics	antennas, cable shielding and composition, electric motor housings, switch cabinets, busbars, capacitors, microchip base material, cooling fin profiles, memory plates for electronic data processing (EDP) systems
Packaging	beverage cans, tubes, spray cans, coffee capsules, menu grill trays, twist-off bottle caps, packaging for medicines
Miscellaneous	sport and leisure equipment, household items, furniture parts, effect pigments for paints, bicycles, motorbikes, regatta sailboat masts

2.2.1.1.2 STEEL AND STAINLESS STEEL

Steels are alloys of iron and carbon with other metals and typically have a carbon content of 2% or less, with some alloys containing no carbon at all. The physical properties of steel are mainly influenced by the interaction between the chemical composition of the steel, the thermal treatment of the steel and the method used to remove oxygen from the steel in the fabrication process.

FIGURE 19

Example of steel pipes

The factors that have the most significant effect on the mechanical properties of stainless steel are its chemical composition and its crystalline microstructure. Stainless steel is an alloy of iron and chromium with at least 10.5% chromium and may contain other alloying elements. Some of the other commonly used alloying elements include manganese, silicon and nickel. Carbon and nitrogen may also be present. However, unlike the metallic alloying elements, which replace an iron atom in the metallic crystalline structure, carbon and nitrogen occupy the interstitial spaces between the metallic atoms.

TYPICAL APPLICATIONS OF STEEL	
Automotive	body, engines, gears, powertrain
Railway	rails, chassis, wheels, powertrain
Construction	bridges and building construction, steel cables in reinforced concrete
Consumer Goods	pots, knives, cutlery, cooker, refrigerator, furniture
Industry	pumps, cranes, conveyors, turbines or milling machines, components
Process Industries	pipes and chemical apparatus, pressure vessels
Miscellaneous	sports and leisure equipment

2.2.1.2 PLASTIC

Plastics are becoming increasingly important in industry because of their versatile properties. A plastic (raw material, additives and production) is often selected as the most suitable material for the desired application due to its combination of machinability, hardness, elasticity, tensile and yield strength, temperature and heat resistance, environmental resistance and chemical resistance. An advantage of plastics over metals is their low weight, but they have limitations in mechanical and thermal stability by comparison; for example, very thin films of plastic can be difficult to bond. Figure 20 describes three main groups of plastics – standard plastics, engineering plastics and high-performance plastics – and their core representatives. For more detailed information regarding plastics, see the *Loctite Design Guide for Bonding Plastics.*

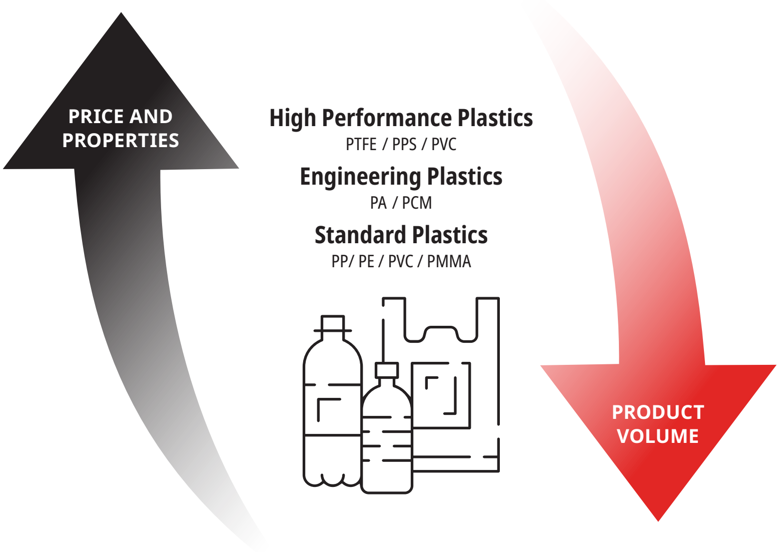


FIGURE 20

The price, property and volume relationship between high performance, engineering and standard plastics

2.2.1.2.1 STANDARD PLASTICS

FIGURE 21

Example of plastic (PE) granulate

Standard plastics include polyvinyl chloride (PVC), polyethylene (PE), polypropylene (PP), polystyrene (PS), acrylonitrile-butadiene-styrene (ABS), and acrylic (PMMA). These account for about 80% of the world's plastic consumption and are best suited for mass production in consumer goods and packaging industries because of their low price. Even though the mechanical properties are inferior to those of engineering plastics, polyolefins (PE and PP), are ideal for specific technical applications because of their chemical resistance and PVC because of its electrical insulation properties.

POLYVINYL CHLORIDE (PVC)

PVC, the most widely used of the vinyl resins, is formed via free radical polymerisation of the vinyl chloride monomer. Unmodified PVC is a hard, brittle, glass-like material which is unsuitable for most engineering applications. However, the addition of plasticisers, such as dioctyl phthalate (DOP), gives PVC sufficient flexibility to be used for many applications. PVC is one of the most economical and versatile plastics in use today. It has become a highly popular construction material, with major applications, including piping and home siding. Specialty grades available include impact modified, filled, pigmented and flame retardant.

TYPICAL APPLICATIONS OF PVC	
Construction	water supply, agricultural irrigation and chemical processing piping, siding, window sashes, gutters, interior mouldings, flooring
Packaging	films for food wrap, bottles, food containers
Consumer goods	furniture parts, wall coverings, upholstery, sporting goods, toys
Electronics	wiring insulation, cables
Medical	tubing, blood and solution bags, dialysis devices, connectors

POLYETHYLENE (PE)

PE is not a high-performance plastic suited for extreme service environments, but rather an extremely versatile and inexpensive resin that has become one of the most popular of all plastics. Almost all of PE's properties vary greatly with changes in density and molecular weight. Low density PE has a relatively low strength and hardness but is flexible, clear, impact, creep and stress-crack resistant, and can have an elongation comparable to some rubbers. High density PE has significantly higher strength, hardness, abrasion and chemical resistance, but it sacrifices some of the properties in which low density PE excels. PEs are not able to withstand high temperatures, but their chemical resistance is excellent for inexpensive, non-engineering resins.

TYPICAL APPLICATIONS OF PE	
Films	shrink bundling, drum and bag liners, ice bags, shipping sacks, cling wrap, snack packaging, diaper liners
Packaging	food and shipping containers, milk, water, antifreeze, household chemical containers, squeeze bottles
Miscellaneous	pipe and chemical drum liners, electric cable jacketing, toys, portable sanitary facilities, commercial storage tanks, envelopes

POLYPROPYLENE (PP)

PP is known for its good mechanical properties, heat and chemical resistance. In addition, PP has the highest flexural modulus of the polyolefins, is among the lightest of the engineering thermoplastics (specific gravity = 0.90) and has excellent moisture resistance. One of the major limitations of PP is its poor impact strength at low temperatures. However, PP/elastomer blends are available with much improved impact resistance. The mechanical properties of PP are highly dependent on its degree of crystallinity. Isotactic PP is harder, stiffer and has a higher tensile strength than atactic PP, while atactic PP exhibits better impact strength and elongation under stress.

TYPICAL APPLICATIONS OF PP	
Fibres	carpet backing, diaper coverstock, rope
Packaging	packaging films, bottles, prescription vials
Appliance	washer agitators, dishwasher components
Miscellaneous	straws, luggage, syringes, toys, storage battery cases

POLYSTYRENE (PS)

PS is known for its optical clarity, rigidity and ability to be processed by all thermoplastic processes. A flexural modulus as high as approximately 3,400 N/mm² (500,000 psi), tensile strength of >55 N/mm² (>8,000 psi) and an elongation generally between 3% and 5% are typical of crystal PS. However, the impact resistance of crystal PS is very low, usually between 0.16 and 0.26 J/cm (0.3 and 0.5 ft-lb/in). Impact resistant grades are available with elongations of up to 50% and notched izod impact strengths as high as 0.26 to 6.35 J/cm (5 ft-lb/in), but the optical clarity and tensile strength decrease. Crystal grades of PS transmit up to 90% of visible light but are succeptible to weathering and UV light degradation.

TYPICAL APPLICATIONS OF PS	
Packaging	processed food and produce containers, foam meat and produce trays
Construction	window mouldings and frames, doors and door frames, footing profiles, structural foam sections for insulating walls
Household	Styrofoam plates, toys, food containers, television housings
Medical	labware, diagnostic equipment, tissue culture flasks, vacuum canisters

ACRYLONITRILE-BUTADIENE-STYRENE (ABS)

ABS offers an excellent combination of toughness and rigidity at a low cost. The typical notched impact strength ranges from 26.5 to 635 J/m (0.5 to 12 ft-lb/in), while typical tensile modulus range from 1,370 to 8,240 N/mm² (200,000 to 1,200,000 psi). In addition to its toughness, ABS has high dimensional stability (which permits tight mould tolerances), a pleasing surface appearance and is easy to process. ABS is a relatively effective electrical insulator and is suitable for secondary insulating applications.

TYPICAL APPLICATIONS OF ABS	
Medical	piercing pins, clamps, filter casings, stopcocks, check valves, blood dialysers
Miscellaneous	appliances, business machines, telephones, luggage, power tools, bathtubs, pipe fittings, toys, faucets, showerheads, sporting goods, automotive applications

ACRYLIC (PMMA)

Transparency equal to glass and outstanding weatherability are acrylic’s most notable properties. Years of testing with sunlight and artificial light sources have resulted in no appreciable yellowing or loss in the physical properties of acrylics. They have good tensile and flexural strength, but even low stress can cause surface crazing if applied for extended periods of time. Acrylics are more rigid than most thermoplastics, but a large, unsupported sheet will deform permanently under a continuous load, even from its own weight. Acrylics are not recommended for high temperature applications, illustrated by their continuous service temperatures of 76°C (170°F) to 88°C (190°F), though annealing can be used to increase this temperature.

TYPICAL APPLICATIONS OF ACRYLIC (PMMA)	
Construction	swimming pools and buildings enclosures, panelling, break-resistant security glazing, tinted sunscreens, domed skylights, lighting fixtures
Automotive	lenses, medallions, nameplates, parts, instrument panels, signals
Household	lavatory and vanity tops, tubs, counters, furniture
Medical	IV systems, blood pumps, filters, y-sites, luers
Miscellaneous	display cabinets, appliances, false fingernails, aviation canopies

2.2.1.2.2 ENGINEERING PLASTICS

Engineering plastics, including polyamide (PA), polyoxymethylene (POM), polycarbonate (PC) and polyethylene terephthalate (PET), account for about 20% of global plastics production. Engineering plastics have better mechanical and thermal properties than standard plastics. They are therefore gaining popularity and are more often selected over traditional materials such as metals. Additional properties include good abrasion resistance, excellent sliding properties, corrosion and chemical resistance, dimensional stability and high temperature stability – in some cases up to 135°C (275°F). The processability and diverse design shape possible, coupled with lightweight properties, also provide an excellent cost-benefit ratio.

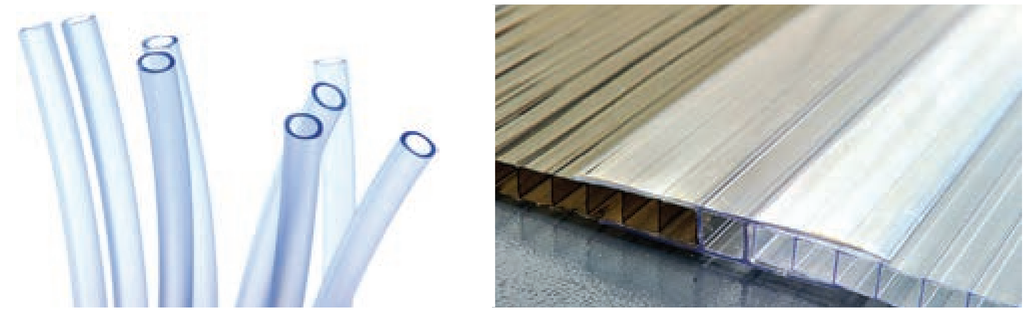


FIGURE 22

Semi-finished products made out of PC or other engineering plastic

Dolas/Getty

POLYAMIDE (PA)

All polyamides absorb moisture from the atmosphere, and the water that enters their structure causes dimensional changes and acts as a plasticiser. These factors must be considered when designing a critical part constructed of PA. The plastic is inexpensive and has excellent tensile strength which explains its widespread use as a fibre. Unfilled PA is biologically inert, and most grades have been cleared for food contact use by the FDA.

TYPICAL APPLICATIONS OF PA	
Automotive	electrical connectors, wire jackets, emission canisters, light duty gears, fan blades, brake fluid and power steering reservoirs, valve covers, steering column housings, emission control valves, mirror housings
Electronic	cable ties, plugs, connectors, coil forms, terminals
Consumer goods	ski boots, ice skate supports, racquetball racquets, ballpoint pens
Miscellaneous	oven cooking bags, gun stocks, air conditioner hoses, brush bristles, sutures, fishing line, mallet heads, combs, furniture parts

POLYOXYMETHYLENE (POM)

POM exhibits high physical strength and excellent creep and impact resistance. Because of its extremely low water absorption rate, the electrical properties and dimensional stability of acetal resins are minimally affected by atmospheric moisture. The dielectric constant of a POM resin varies only slightly over a wide frequency range: its dielectric strength is high and the volume resistivity of >1010 Ωm makes it a good electrical insulator. POM is resistant to solvents, ethers, oils, greases, gasoline and other organic compounds and is especially suited for use with methanol-based fuels. It is resistant to moderate strength acids but is not recommended for use with strong acids. POM homopolymer is highly resistant to wear due to its hard surface and low coefficient of friction (0.1 to 0.3).

TYPICAL APPLICATIONS OF POM	
Automotive and mechanical engineering	gears, miniature gears, switch gears, ball bearing cages; parts of tank caps, fuel pumps and carburettors, loudspeaker grilles (car); snap and spring elements; parts and housings for water pumps, valves, fittings; screws, nuts and bearings for clockworks, components in ‘outsert technology
Electronics	precision parts for telephones, radios, televisions, sound reproduction and fax machines, photocopiers, conductive moulded parts with appropriate filling
Packaging	spray cans, gas lighter tanks, gas ampoules
Consumer goods	fittings, hinges, lock parts, door and window handles, coupling parts for garden hoses, ski binding parts
Miscellaneous	hooks, zips, dry powder inhalers, insulin pens, toothbrushes, toys

POLYCARBONATE (PC)

PC offers a unique combination of outstanding clarity and high impact strength. In addition, it is dimensionally stable and has low flammability. These characteristics make PC well suited for light transmission applications, such as automotive tail-light housings. Because of the low levels of monomers and catalysts used in processing PC, it is generally biocompatible and suited for use in medical applications, where device surfaces may come into contact with blood or other bodily fluids. PC offers limited resistance to chemicals and is soluble in many organic solvents.

TYPICAL APPLICATIONS OF PC	
Packaging	reusable bottles, frozen foods, large water bottles
Food Service	beverage pitchers, mugs, food processor bowls, tableware, microwave cookware
Automotive	lamp housings and lenses, parts, electrical components, instrument panels
Medical	filter housings, tubing connectors, surgical staplers, eyewear
Miscellaneous	bulletproofing, computer housings, aircraft interiors

POLYETHYLENE TEREPHTHALATE (PET)

For almost all injection moulding applications of PET, the PET will be either glass or mineral filled. Reinforced PET - the stiffest of all the commonly used thermoplastics - has high tensile strength, excellent heat resistance, outstanding weatherability and minimal water absorption. Although reinforced PET only has moderate impact resistance, impact resistant grades are available that offer increased notched izod impact strength. Reinforced PET has a high dielectric strength, which remains constant or increases with temperatures up to 149°C (300°F). PET is chemically resistant to most chemicals over a wide range of temperatures, including motor fuels, oils and hydrocarbon solvents.

TYPICAL APPLICATIONS OF PET	
Automotive	cowl vent grilles, sunroof rails, wiper blade supports
Electrical	computer fans, fuse holders, insulated housings
Packaging	soft drink containers, packaged food containers

POLYBUTYLENE TEREPHTHALATE (PBT)

The most notable properties of PBT are its chemical resistance and mechanical properties. PBT offers good resistance to water, weak acids and bases, ketones, alcohols, glycols, ethers, aliphatic hydro-carbons and chlorinated aliphatic hydrocarbons at room temperature. At temperatures up to 140°F (60°C), PBT is resistant to transmission fluid, brake fluid, gasoline and motor oil. It is not recommended for use in strong bases at any temperature or in aqueous mediums at temperatures above 125°F (52°C). PBT has good tensile strength, high dimensional stability and a lubricity which makes it highly resistant to wear. It has a relatively low heat deflection temperature, but glass filled grades can increase this to over 400°F (204°C).

TYPICAL APPLICATIONS OF POLYBUTYLENE TEREPHTHALATE (PBT)	
There are many different grades of PBT. Surface preparation is sometimes required.	
Automotive	brake system parts, distributor caps, fuel injection modules, grille opening panels
Electronics	connectors, switches, relays, TV tuners, motor housings, fuse cases, light sockets
Medical	specialty syringes, irrigation and wound drainage systems, check valves, catheter housings
Miscellaneous	industrial zippers, power tool housings, hair dryers, calculators, cooker-fryer handles, iron and toaster housings, food processor blades

2.2.1.2.3 HIGH-PERFORMANCE PLASTICS

High-performance plastics include polytetrafluoroethylene (PTFE), polyphenylene sulfide (PPS), polyphenylsulfone (PPSU), polyetheretherketone (PEEK), polyethersulfone (PES), styrene-acrylonitrile (SAN) and polyvinylidene difluoride (PVDF). These plastics play a minor role (approx. 0.2%) in global plastics production. Since one or more properties are optimised for specific applications in these types of plastics, they are clearly distinguished from engineering plastics. Temperature resistance is one of the outstanding properties of high-performance plastics, and it is used in applications up to a permanent service temperature of 260°C (500°F). Some high-performance plastics also offer excellent resistance to extremely low temperatures – as low as -200°C (-330°F) – as well as high resistance to chemicals, radioactive radiation and other environmental influences. Other superior properties include extremely high wear resistance and electrical insulation.

FIGURE 23

Products made of PTFE

blackcatstudio/Getty

POLYTETRAFLUOROETHYLENE (PTFE)

Although the tensile strength, wear resistence and creep resistance of PTFE are low compared to other engineering thermoplastics, it has excellent impact strength, a coefficient of friction that is lower than almost any other material, a high oxygen index and it does not support combustion. In addition, PTFE has useful mechanical properties at temperatures ranging from -200°C to 260°C (-330°F to 500°F). It has exceptional chemical resistance to most organic compounds, including solvents, strong acids and strong bases. PTFE is an outstanding electrical insulator, and it has a low dielectric constant and loss factor which are both stable over a wide range of temperatures and frequencies.

TYPICAL APPLICATIONS OF PTFE	
Electrical	high temperature, high-performance wire and cable insulation, sockets, pins, connectors
Mechanical	bushings, rider rings, seals, bearing pads, valve seats
Non-stick	home cookware, tools, food processing equipment coatings
Miscellaneous	conveyor parts, packaging, flame-retardant laminates, chemical processing equipment

POLYPHENYLENE SULFIDE (PPS)

The most notable properties of PPS are its thermal stability, inherent flame resistance and outstanding chemical resistance. PPS also has good mechanical properties that remain stable during both long- and short-term exposure to high temperatures. Although the high tensile strength and flexural modulus associated with PPS decrease somewhat with increasing temperature, they level off at approximately 121°C (250°F), and moderately high mechanical properties are maintained up to 260°C (500°F). PPS also exhibits a significant increase in its elongation and toughness at elevated temperatures. Although PPS has a low impact strength, glass fibres can be added for applications requiring high impact strength and dielectric properties. Glass and mineral fillers are also used for electrical applications requiring a high arc resistance and low track rate.

TYPICAL APPLICATIONS OF PPS	
Telecommunications	control cabinets, cable splice boxes, wire board frames
Automotive	grilles, spoilers, wheel covers, fuse blocks
Business	personal computers, printers
Machines	bases, video display terminals

POLYPHENYLSULFONE (PPSU)

PPSU is an amorphous material known for its high toughness, high flexural and tensile strength, excellent hydrolytic stability and good resistance to chemicals and heat. Compared to polysulfone (PSU) and PES, it has superior mechanical properties but is less commonly used due to its relatively high cost. PPSU has a high glass transition temperature and low moisture absorption, making it a good candidate material for medical applications.

TYPICAL APPLICATIONS OF PPSU	
Medical	test implants/artificial joints for hip, knee, shoulder, medical device handles

POLYETHERETHERKETONE (PEEK)

PEEK is a high-performance thermoplastic that is well suited to high temperature environments. PEEK also has good mechanical properties, including a flexural modulus among the highest of all thermoplastics. The addition of fillers to PEEK typically increases both its modulus and thermal stability. PEEK is suitable for applications that will see intermittent exposure to temperatures up to 315°C (600°F) and has a maximum continuous service temperature of approximately 250°C (480°F).

TYPICAL APPLICATIONS OF PEEK	
Aerospace	wire and cable insulation, coatings, EMI/RFI shields
Miscellaneous	high temperature bearings, compressor components, nuclear power plant and oil well applications, military equipment

POLYETHERSULFONE (PES)

The most notable properties of PES are its transparency, good mechanical properties and outstanding thermal stability. Unfilled PES has a useful life of four to five years at 199°C (390°F) and approximately 20 years at 180°C (360°F). Moreover, the mechanical and electrical properties of PES show low sensitivity to temperature change and load. In addition, the mechanical properties of PES at elevated temperatures can be significantly increased by annealing. PES has a low smoke emission and can withstand long-term exposure to both air and water at elevated temperatures.

TYPICAL APPLICATIONS OF PES	
Electrical	multipin connectors, coil formers, printed circuit boards
Miscellaneous	radomes, pump housings, bearing cages, hot combs, medical trays

STYRENE-ACRYLONITRILE (SAN)

The major benefits of SAN are its stiffness, strength and clarity. However, like PS, SAN has a low impact strength. The use of reinforcing fillers, such as glass fibre, can be used to increase its impact strength as well as its heat resistance, hardness and modulus. The continuous service temperature of SAN is dependent on the load and specific chemical environment to which it is exposed, normally varying between 49°C (120°F) and 82°C (180°F).

TYPICAL APPLICATIONS OF SAN	
Appliances	knobs, refrigerator compartments, blender and mixer bowls
Electronics	cassette cases, meter lenses, tape windows
Medical	syringe components, blood aspirators, dialyser housings
Packaging	cosmetic containers, closures, bottles, jars
Miscellaneous	safety glazing, battery cases, typewriter keys, pen and pencil barrels

POLYVINYLIDENE DIFLUORIDE (PVDF)

PVDF is used in applications requiring the highest purity, as well as resistance to solvents, acids and hydrocarbons. PVDF has a low density (1.78 g/cm^3) compared to other fluoropolymers such as PTFE. Furthermore, this material possesses excellent piezoelectric properties, thermal stability and mechanical strength. It also offers good processability, making it suitable for a wide range of demanding applications.

TYPICAL APPLICATIONS OF PVDF	
Food service, medical and chemical plant engineering	high temperature valves, filter plates, fittings, piping and coil formers

2.2.1.3 RUBBER AND THERMOPLASTIC ELASTOMERS

FIGURE 24

Different parts of rubber

Natural Rubber (NR) and thermoplastic elastomers are stable, resilient, easy to work with and highly durable materials. Elastomers are used where their characteristic properties are required, i.e. when rubber-elastic behaviour in the application temperature range is necessary. A distinction can be made between natural rubber (NR) and synthetic rubber, such as styrene-butadiene rubber (SBR), chloroprene rubber (CR), butyl rubber (IIR), ethylene propylene diene rubber (EPDM), butadiene-acrylonitrile rubber (NBR) and silicone rubber (Q). Even though synthetic rubbers have been further developed in recent years, the properties of NR remain unrivalled, especially in terms of permanent elasticity, cold elasticity and abrasion resistance.

According to DIN 7724 and ISO 472, further distinctions are made between elastomers and thermoplastic elastomers.

- Elastomers: rubber elasticity is present at temperatures below 20°C (70°F).
- Thermoplastic elastomer: rubber elasticity is present above 20°C (70°F) up to the decomposition temperature.

The following are typical properties of rubber and thermoplastic elastomers:

- They are elastic.
- They are not meltable.
- They do not have thermoplastic properties (thermoplastic elastomers are an exception to this).
- They are not soluble in solvents.
- They can swell when they come into contact with solvents.

For more detailed information regarding rubbers, see the *Loctite Design Guide for Bonding Rubber and Thermoplastic Elastomers.*

NATURAL RUBBER (NR)

Rapid crystallisation on stretching gives NR its exceptional tensile strength, tear strength and abrasion resistant properties. The tensile strength of unfilled vulcanates ranges from 17 to 24 N/mm² (2,500 to 3,500 psi), while fillers can increase above 31 N/mm² (4,500 psi). The resilience of NR is excellent. At large strains, the fatigue life of NR is better than SBR. At low strains, the opposite is true. The strength characteristics of NR decrease with increasing temperature. However, the strength at the temperature of NR is normally superior to that of other elastomers. NR has excellent processing properties and can be processed using a variety of different techniques.

TYPICAL APPLICATIONS	
Industrial	hoses, conveyor belts, gaskets, seals
Engineering	springs, mountings, bushings
Latex	gloves, condoms, carpet backing, threads

STYRENE BUTADIENE RUBBER (SBR)

SBR is predominantly used in the manufacture of tyres due to its superior abrasion resistance and traction. For tyre applications, the glass transition temperature (Tg) is critical. If the Tg is too high, the tyres will become brittle in cold conditions. If the Tg is too low, the tyre traction is compromised. Consequently, any rubber with a Tg that is not between -50 and -70°C (-58 and -94°F) must be mixed with at least one other rubber for tyre applications. The processing temperature of the SBR has a large effect on the resulting properties of the material. Compared to hot SBR, cold SBR has better abrasion resistance and dynamic properties, as well as a higher capacity to be extended, compared to hot SBR.

TYPICAL APPLICATIONS OF SBR	
Automotive	tyres, hoses, belts
Industrial	foamed products, extruded goods
Consumer	shoe soles, waterproof materials
Miscellaneous	adhesives, asphalt

CHLOROPRENE RUBBER (CR)

CR is a synthetic rubber that is also known by the trade name Neoprene. It has excellent physical properties, weather resistance and thermal resistance, and it can retain properties at low temperatures. It maintains a good balance of these properties, including good chemical stability over a wide operating temperature range.

TYPICAL APPLICATIONS OF CR	
Aerospace	gaskets, seals, de-icers
Automotive	timing belts, window gaskets, fuel lines, covers, cable jacketing, spark plug boots, hoses, joint seals
Industrial	pipeline pigs, gaskets, hoses, power, transmission belts, conveyor belts, escalator handrails
Electronics	wire and cable jacketing
Miscellaneous	sponge shoe soles, foam cushions

BUTYL RUBBER (IIR)

The saturation of the polymer backbone and lack of reactive groups result in a combination of valuable properties that have made butyl polymers one of the most widely used synthetic elastomers. The aliphatic nature of the polymer gives it good resistance to ozone, UV light, moisture and mineral acids. This nature also contributes to its thermal resistance, which is limited more by the type of crosslink system used than by the stability of the polymer backbone. IIR formulations cured using sulphur tend to degrade after long-term exposure to temperatures above 150°C (300°F). Formulations that utilise the phenol formaldehyde resin cure system offer much better thermal resistance.

TYPICAL APPLICATIONS OF IIR	
Automotive	tyre inner liners, inner tubes, radiator hoses, belts
Electronics	electrical insulation
Industrial	conveyor belts, curing bladders, membranes, freezer gaskets, tank linings, steam hose, diaphragms
Miscellaneous	dock fenders

ETHYLENE PROPYLENE DIENE (MONOMER)

EPDM is known for its superior resistance to ozone and oxidation, as well as its relatively low cost. The low cost of compounded EPDM stems from its potential for high loading with low-cost fillers. The aliphatic nature of the backbone results in the excellent weatherability of EPDM and makes it extremely stable in colour. EPDM also exhibits good electrical properties due to its non-polar backbone and the amorphous regions of the polymer. EPDM responds well to loading, developing high tensile, tear and abrasion properties. EPDM has favourable thermal properties and can, therefore, be considered for a multitude of potential applications. Silicone-modified EPDM represents a unique combination of the benefits offered by silicone and EPDM rubbers. The performance properties of silicone-modified EPDM are best understood in terms of the properties of each of the pure components. In general, it has the good mechanical properties of EPDM rubber with the improved thermal resistance of silicone elastomers.

TYPICAL APPLICATIONS OF EPDM	
Automotive	hoses, belts, cable insulation, boots, seals, weatherstrip
Consumer	garden hose, roof sheeting, ditch liners, coated fabrics
Electronic	cable covers, underground wire, power cable insulation

BUTADIENE-ACRYLONITRILE RUBBER (NBR)

Nitrile rubbers, also known as nitrile butadiene rubbers or butadiene acrylonitrile rubbers (NBR), are known for their superior high and low temperature performance and their exceptional oil, gasoline and solvent resistance. These properties, coupled with their good abrasion resistance, water resistance and compression sets make them suitable for a wide variety of applications. Their thermal resistance allows them to be used at service temperatures ranging from -45 to 149°C (-49 to 300°F). Since the monomer ratio has a large effect on the properties of the elastomer, the ratio is dictated by its end use. For superior tensile properties or oil resistance, a high level of acrylonitrile should be used. If low temperature performance is paramount, a low acrylonitrile level is more appropriate.

TYPICAL APPLICATIONS OF NBR	
Automotive	seals, hoses, tubing, belts, electrical jacketing, gaskets
Consumer	shoe products, coated fabrics, flooring
Miscellaneous	adhesives, cements, PVC and ABS additives

SILICONE RUBBER (Q)

The unique properties of polydimethyl siloxane elastomers arise primarily from the high bond energy of the silicon oxygen bonds along the backbone and from the non-polar nature of the two methyl groups, which are pendant from each of the silicon atoms. The result is an elastomer with good flexibility and compression set resistance over a wide temperature range. The silicon oxygen bond results in a polymer with excellent resistance to UV and ozone, as well as long-term exposure to temperatures of 204°C (400°F) and intermittent exposure to temperatures as high as 316°C (600°F). More importantly, silicone elastomers retain much of their tensile strength and compression set resistance at these high temperatures.

TYPICAL APPLICATIONS OF Q	
Automotive	hoses, gaskets, seals, ignition cable insulation
Industrial	adhesives, high temperature gaskets, seals, sponges
Medical	implantable devices, tubing

2.2.1.4 COMPOSITES

COMPOSITES

The development, design and manufacturing of composite materials is one of the most important advances in the history of materials. Composites are multifunctional materials with distinctive mechanical and physical properties that can be tailored to meet the requirements of a particular application. Many composites exhibit great resistance to wear, corrosion and high temperature exposure. These unique characteristics provide design opportunities that are not possible with many conventional materials. Composite material technology also makes it possible to use an entire class of solid materials such as ceramics, in applications for which monolithic versions are unsuited because of their high strength but poor mechanical and thermal shock resistance. Furthermore, many manufacturing processes for composites are well adapted to the fabrication of large, complex structures, which allows for the consolidation of parts and reduces manufacturing costs. Composite materials offer a high strength-to-weight ratio and exhibit exceptional properties such as high durability, stiffness, damping properties, flexural strength, corrosion, wear, impact and fire resistance.

TYPICAL APPLICATIONS	
Aerospace	aircraft structures and mechanical components
Automotive and railway	brakes, drive shafts, flywheels, tanks, pressure vessels, dimensionally stable components
Industrial	internal combustion engines, machine components, thermal management, electronic packaging
Process industries	equipment requiring resistance to high temperature, corrosion, oxidation and wear, offshore and onshore oil exploration and production
Miscellaneous	marine structures, sports and leisure equipment, ships and boats, biomedical devices

2.2.1.5 GLASS

Glass has been made and used by humans for thousands of years, although the industrial production and use of glass only started in the middle of the 19th century. Glass is a solid, transparent and amorphous material consisting mainly of silicon dioxide. It has many favourable properties that make it significant, such as transparency, many possibilities of shape and colour, resistance to most chemicals, low thermal conductivity and low electrical conductivity. However, glass is also susceptible to impact and is brittle. Soda-lime glass, lead glass and borosilicate glass make up the bulk of today's glass production. Glass is also divided according to the form of glass, including flat glass (building), hollow glass (bottles, drinking vessels), glass tubes (laboratory equipment), foam glass, glass wool, glass fibres and coloured glass.

FIGURE 25

Glass

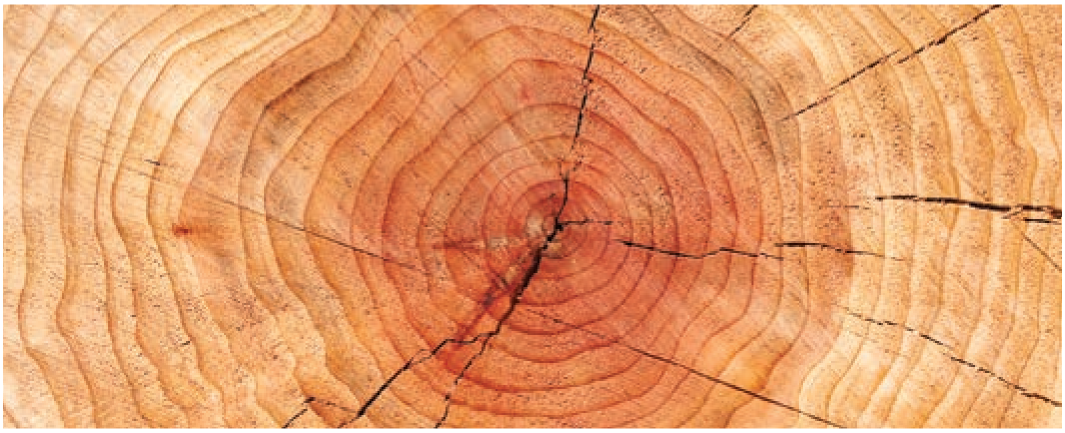
TYPICAL APPLICATIONS	
Construction	flat glass, glass wool
Automotive	headlights, windscreens
Consumer goods	furniture parts, tableware, lighting, cooking utensils
Medical	laboratory glass
Packaging	container glass
Electronics	fibres for printed circuit boards, substrate glass for displays, optical glass fibre
Fibres	textile glass fibres, reinforcement fibres for plastics
Miscellaneous	lenses, art glass, decorative enamels, chemical equipment

2.2.1.6 WOOD

Wood has been used as a building material and for tools since the earliest times of humanity and is still indispensable today. Wood is not only ecologically sensible, as it is a renewable raw material, but it also offers desirable mechanical properties and good workability. A distinction is made between hardwood and softwood. It is available both as solid wood and in mixed forms, such as cross-laminated timber, laminated plywood, multi-layer boards and fibreboards.

FIGURE 26

Wood



MadamLead/Getty

TYPICAL APPLICATIONS

Apart from paper production and energy generation, wood is mainly used in the construction, furniture (including flooring) and packaging industries.

Construction	building material, scaffolding
Consumer goods	furniture, flooring, tableware, cooking utensils, toys
Packaging	boxes, pallets
Miscellaneous	art, decoration, playgrounds

2.2.1.7 OVERVIEW OF SUBSTRATE PROPERTIES

Table 3 presents an overview of the substrate properties for comparison and Table 4 provides an overview of substrate combinations as they relate to joining methods.

TABLE 3

Comparative substrate properties

		MECHANICAL PROPERTIES				ELECTRICAL PROPERTIES
		Density [g/cm^3]	Tensile Strength [N/mm^2]	Elongation at Break [%]	E-modulus [N/mm^2]	Specific Electrical Resistance [Ωmm^2/m]
METAL	(Annodised) Aluminium	2.7	60-700	45-60	70,000	0.0028
	(Stainless) Steel	7.9	300-1,250	6-40	210,000	0.100-0.200
PLASTIC	Standard	0.9-1.4	11-80	3-700	200-3,200	$>10^{16}$
	Engineering	1.0-1.4	27-86	1-300	690-8,200	$>10^{10}$
	High Performance	1.1-2.4	7-200	2-650	300-31,000	$>10^{17}$
	Rubber	0.9-1.6	6-30	450-800	10-5,000	$>10^{13}$->10^{16}
	Composites	1.5-2.1	330-1,100	1-4	24.000-100,000	n/a
	Glass	2.5-2.6	30-100	0	70,000	$>10^{13}$->10^{17}
	Hardwood and Softwood	0.4-0.8	11-36[1]	n/a	9,000-17,000	$>10^{10}$->10^{15}

		PHYSICAL PROPERTIES		THERMAL PROPERTIES				
		Humidity Absorption [%]	Temperature Range [C°]	Surface Energy [mN/m]	Chemical Resistance	Corrosion Resistance	Transparency	UV Resistance
METAL	(Annodised) Aluminium	0	up to 350	840	good	good	no	very good
	(Stainless) Steel	0	up to 1,100	700-1,100	good	good	no	very good
PLASTIC	Standard	0-2	-40 up to 100	29-51	good	very good	as well as	good
	Engineering	0.3-3.0	-100 up to 135	33-54	good	very good	as well as	good
	High Performance	0.01-1.10	-200 to 260	15-47	good	very good	as well as	good
	Rubber	n/a	-50 up to 300	n/a	moderate	very good	no	moderate
	Composites	n/a	up to 400	n/a	good	good	no	good
	Glass	0	up to 850	45-500	very good	very good	yes	very good
	Hardwood and Softwood	n/a	up to 60	40-50	n/a	n/a	no	very good

(1) Parallel to the fiber direction

Note. The information given is without guarantee and the values given are only approximate values. For more detailed information, please refer to the respective manufacturer's specifications.

2.2.1.8 OVERVIEW OF POSSIBLE SUBSTRATE COMBINATIONS AND JOINING METHODS

TABLE 4

Overview of possible substrate combinations and joining methods

		METAL										PLASTICS														
		(ANNODISED) ALUMINIUM					(STAINLESS) STEEL					STANDARD					ENGINEERING					HIGH PERFORMANCE				
		Welding	Screwing	Riveting	Clipping	Bonding	Welding	Screwing	Riveting	Clipping	Bonding	Welding	Screwing	Riveting	Clipping	Bonding	Welding	Screwing	Riveting	Clipping	Bonding	Welding	Screwing	Riveting	Clipping	Bonding
METAL	(Annodised) Aluminium	✓	✓	✓	✗	✓																				
	(Stainless) Steel	✗	✓	✓	✗	✓	✓	✓	✓	✗	✓															
PLASTIC	Standard	✗	✓	✓	✓	✓	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓										
	Engineering	✗	✓	✓	✓	✓	✗	✓	✓	✓	✓	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓					
	High Performance	✗	✓	✓	✓	✓	✗	✓	✓	✓	✓	✗	✓	✓	✓	✓	✗	✓	✓	✓	✓	!	✓	✓	✓	✓
	Rubber	✗	!	!	!	✓	✗	!	!	!	✓	✗	!	!	!	✓	✗	✓	!	!	✓	✗	!	!	!	✓
	Composites	✗	✓	✓	✓	✓	✗	✓	✓	✓	✓	✗	✓	✓	✓	✓	✗	✓	✓	✓	✓	✗	✓	✓	✓	✓
	Glass	✗	✓	✗	✗	✓	✗	✓	✗	✗	✓	✗	✓	✗	✗	✓	✗	✓	✗	✗	✓	✗	✓	✗	✗	✓
	Hardwood and Softwood	✗	✓	✗	✗	✓	✗	✓	✗	✗	✓	✗	✓	✗	✗	✓	✗	✓	✗	✗	✓	✗	✓	✗	✗	✓

		RUBBER					COMPOSITES					GLASS					HARDWOOD AND SOFTWOOD				
		Welding	Screwing	Riveting	Clipping	Bonding	Welding	Screwing	Riveting	Clipping	Bonding	Welding	Screwing	Riveting	Clipping	Bonding	Welding	Screwing	Riveting	Clipping	Bonding
METAL	(Annodised) Aluminium																				
	(Stainless) Steel																				
PLASTIC	Standard																				
	Engineering																				
	High Performance																				
	Rubber	✗	!	!	!	✓															
	Composites	✗	✓	!	!	✓	✗	✓	✓	✓	✓										
	Glass	✗	✓	✗	✗	✓	✗	✓	✗	✗	✓	!	✓	✗	✗	✓					
	Hardwood and Softwood	✗	✓	✗	✗	✓	✗	✓	✗	✗	✓	✗	✓	✗	✗	✓	✗	✓	!	✗	✓

✓ possible, common practice ! possible to a limited extent, not usual ✗ not possible

Note. The table is only a selection of possible material and joining combinations, and there is no claim to completeness.

2.2.1.9 KEY SUBSTRATE CONSIDERATIONS

When selecting a material for a given application, it is critical to consider all aspects of operation and be cognisant of the potential impact of all foreseen conditions acting at their peak simultaneously. Not only will the substrate need to resist environmental factors and operational loading and forces, but it will also need to meet the production and processing requirements defined during the design and prototyping phases. The following are some of the core considerations for selecting a material:

- Different substrates are being joined
- The force distribution over the assembly (i.e. spot welding)
- Differential thermal expansion coefficients
- The chemical resistance of substrates
- The temperature resistance of the substrates/joints
- Preventing substrate or component damage (altering the characteristics of the substrate)

2.2.2 CHOICE OF ASSEMBLY TYPE

Various joining techniques are used to assemble materials in a wide range of ways. As some of these methods join components permanently and others create temporary joints, joining is divided into two groups: permanent and temporary. Permanent (non-demountable) joints are separated only by destroying either the joined substrates or the connecting element. As the name suggests, these joints are permanent and usually offer noise, vibration and harshness (NVH) improvements and leak-proof joining. Since permanent joints are not disassembled easily, inspection, repair and replacement are complex and costly. Often non-destructive testing is carried out on permanent joints for inspection of assembly. Permanent joints are suitable for applications in which disassembly is usually not required during service life. Welding is a prime example in this category. Riveted joints, soldering, brazing and adhesive bonds are also permanent joints. However, riveted joints and spot welding can only provide an NVH-optimised and leak-proof joint in conjunction with an adhesive. Figures 27 and 28 show two types of permanent joints.

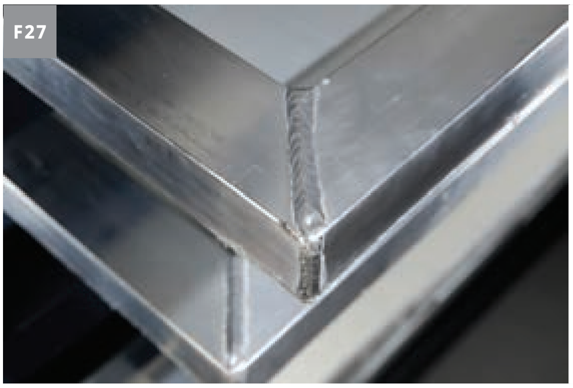


FIGURE 27

Welding

FIGURE 28

Adhesive lamination bonding

Temporary (de-mountable) joints can be detached without destroying the joined parts or the connecting element. Easy disassembly makes inspection and maintenance very easy, fast and cost-efficient. However, temporary joints may not be as strong as a permanent joint. Temporary joints are suitable where frequent separation of assembled components is required. Destructive (mechanical) testing is not needed for the inspection of joints. Temporary connections (see Figures 29 and 30) include mechanical fasteners (screws, bolts), press-fits, keys and pins. Adhesive bonding can also be considered a temporary joining method in some cases. Adhesives can be used in conjunction with mechanical fasteners to make a temporary connection more durable; the adhesive can seal the joint and improve the physical and mechanical properties of the assembly. Figures 29 and 30 demonstrate the application of adhesives for threadlocking of bolted fasteners instead of nuts with nylon inserts, for example, and a press-fit of cylindrical assemblies. Adhesive bonding can distribute stress within a joint more evenly than other standard joining methods.


F29

FIGURE 29

Bolted fastener


F30

FIGURE 30

Cylindrical press fit augmented with adhesive

In addition, permanent adhesive joints can become semi-permanent, i.e. the connection will be non-demountable until one of the following specific conditions is met:

Temperature influence. The joint disassembly temperature must be significantly higher or lower than the recommended operating temperature specified for the adhesive. For example, LCD glass replacement for mobile devices is usually completed at low temperatures using a freezing machine. The phone can be disassembled by freezing and breaking the adhesive material between joined parts while in a frozen state. When the temperature changes, a phase transition occurs in the adhesive and its structure changes. Thermal stresses occur within the joint due to different thermal coefficients of linear expansion for both the bonded materials and the adhesive.

Chemical influence. Upon exposure to harsh chemicals, particularly strong acids, strong bases and harsh solvents, the adhesive layer may be sufficiently degraded that an assembly may become demountable.

Mechanical influence. The application of various loads without damaging the base material (substrate) can make an adhesive joint fail. An important part of mechanical influence is the load application speed influence, which reflects the failure mode of an adhesive joint in the test duration (lifetime of the part), the separation rate of the substrates (speed of movement) and the direction of loading (i.e. stress). When a force acts quickly (see Figure 31), elastomeric adhesive joints can break down and display adhesion failure. This happens because when a separation force is applied at a high speed over a short period, an elastomer works as an elastic body, and the weakest connections are adhesive bonds. At the same time, with slow movement (see Figure 32) or constant stress, such adhesives tend to creep due to the increased deformability of elastomers compared to more rigid adhesives. Under these conditions, the internal strength of the polymer (cohesive strength) can be lower than the adhesion strength to the substrates. Therefore, failure will occur within the adhesive bulk and a cohesive failure mode is observed. Rigid adhesives perform differently under conditions where a load is applied over a period of time. Instead of the stress concentrations being present within the adhesive bulk, such as elastomeric adhesives, they are localised at the edges of the bond area and throughout the peripheral fillets. Rigid adhesives and joining methods are known to display increased tensile strength with higher load speeds. However, the suitability of an adhesive or joining method must consider the potential movement between the joined substrates and not just the speed at which the given load is applied. Under high-movement conditions (relative movement of joined parts, not dynamic loading or vibration experienced during operation), a flexible joining method can offer a more robust and durable joint assembly than one that utilises a rigid solution.

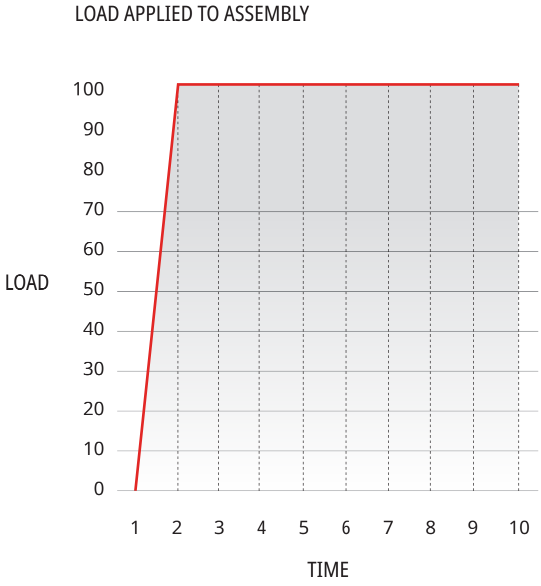


FIGURE 31

Load application speed graph at high speed

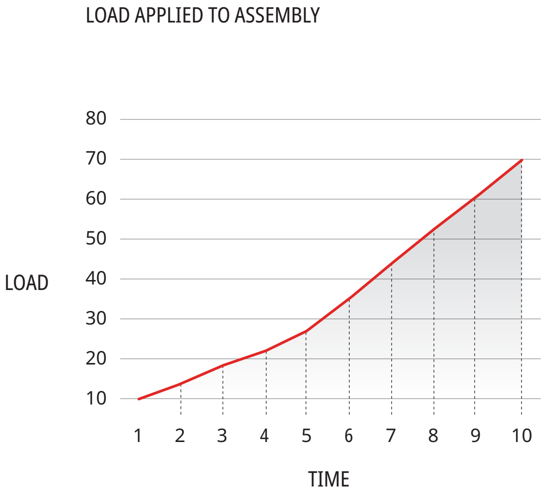


FIGURE 32

Load application speed graph at low speed

In most cases, elastic adhesives are cut to disassemble a joint using tools such as a string or a knife. Such adhesive cutting technology is used to remove an old windscreen in a car.

Before starting the design of a component or assembly, it is necessary to determine if the connection is required to be permanent or temporary. The flowchart in Figure 33 describes the decision-making process in detail. It is important to remember that many joining methods can be temporary and allow for separation or removal and that removability is not an exclusive property of mechanical fasteners. An adhesive-bonded joint can be transformed from permanent to semipermanent, as described above. However, it is also necessary to take into account the requirements for the strength of the joint. Welded joints are very strong, but it is impossible to weld dissimilar materials, and the microstructure and properties of the base material change under the influence of the generated heat. The resulting microstructure affects both the strength of the welded joint and the strength of the material. The use of an adhesive with an appropriate joint design can help to ensure that the finished assembly meets the defined strength requirements.

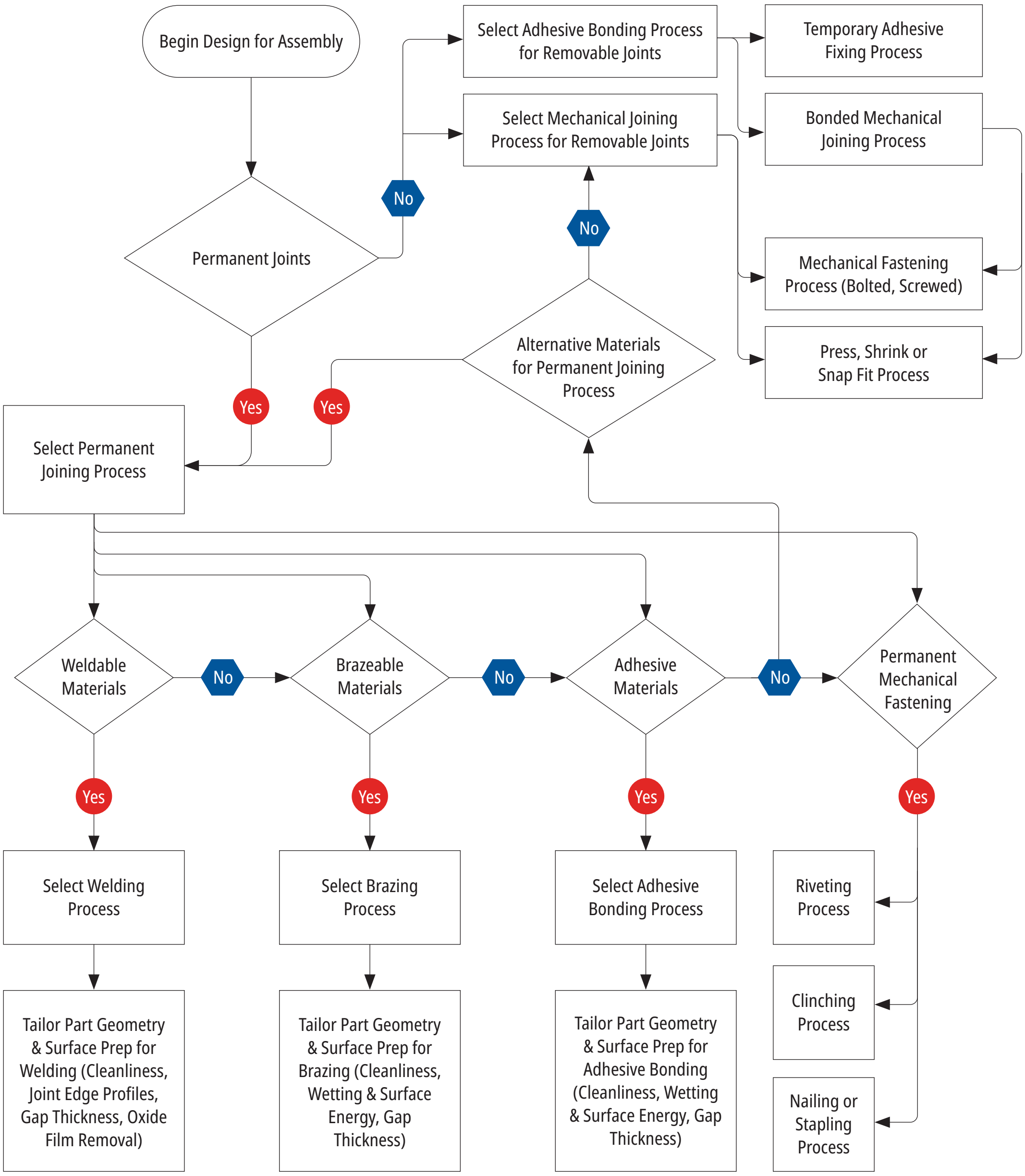


FIGURE 33

Joining method selection process flow chart

2.2.3 OPERATING CONDITIONS

2.2.3.1 ENVIRONMENTAL FACTORS

Regardless of the type of joining method ultimately selected, one of the most important considerations is the environment or surroundings to which the joint and substrate materials will be subjected. Forces acting on the materials and assembly are important to consider. The selected substrates and joining method must carry the maximum expected load, resist fatigue or cyclic stresses and handle the operating conditions experienced during the operation.

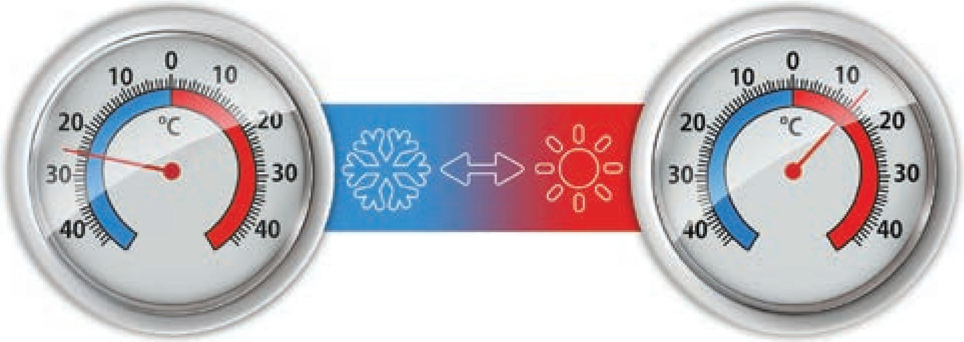
Cyclic stresses, particularly slow ones, are more damaging to materials and joined assemblies than a steady stress. The substrates selected for a particular application must be able to resist these loads and stresses after sustained exposure and under any severe environmental factors encountered during the life of the assembly. Heat and humidity are common yet highly damaging environmental factors for many materials and joining methods.

2.2.3.2 TEMPERATURE CHANGES AND THERMAL CYCLING

Temperature changes can have a significant impact on materials and the selected joining method. Consideration must be given to the average operating temperature as well as the potential range of temperatures the assembly may be exposed to during its lifetime.

FIGURE 34

Understanding the influence of temperature is critical for success



Significant impacts of elevated temperatures are the expansion, softening and relaxation of materials. When designing components, it is critical to observe the capabilities and known resistance of the substrates. For example, heating systems commonly use metallic components because of their ability to withstand high operating temperatures while offering the necessary mechanical performance. Applications that combine the need for rigidity, high strength and high temperature resistance typically limit the use of polymers, rubbers, wood and glass. Understanding how a material will perform under specific or expected conditions is vital.

FIGURE 35

Effects of thermal expansion on dissimilar materials

TABLE 5

Coefficients of linear thermal expansion of common materials

SUBSTANCE	Aluminium	Brass	Copper	Steel	Silver	Gold
(K^-1)	2.4×10^{2}	1.9×10^{2}	1.7×10^{2}	1.2×10^{2v}	1.93×10^{2}	1.3×10^{2}
SUBSTANCE	Platinum	Tungsten	Glass (Pyrex)	Glass (Ordinary)	Concrete	
(K^-1)	8.6×10^{2}	0.4×10^{2}	0.4×10^{2}	0.9×10^{2}	1.2×10^{2}	

In addition to the change in the physical properties of substrates at elevated temperatures, it is important to consider the expansion of materials and ensure that the maximum and minimum permissible change in dimensions is within the scope and capabilities of the intended application. Thermal expansion and contraction can have a greater impact and require further consideration when joining dissimilar materials. It is also important to check the differential of thermal expansion for each material and calculate the maximum dimensional change for each part to confirm the feasibility of the proposed material combination. Over time, repeated condition cycles that vary the dimensions and properties of a material can be translated into a permanent change. Metal parts, such as railway tracks, are constantly exposed to external environments and are subjected to repeated thermal cycles and variable conditions. Despite deliberate gaps being left between joint sections of the track to accommodate thermal expansion, they can creep dimensionally and become permanently distorted after repeated exposure to thermal cycles. This cyclic expansion and contraction can cause gaps and misalignments to become apparent and pose significant safety risks. Identifying how critical a part is and understanding the effects of failure play a big part in the selection of materials and subsequent joining methods.

FIGURE 36

Effects of thermal expansion and contraction on railway tracks

Externally acting forces and applied loads can lead to fatigue, deformation, weakening and degradation of parts and materials, which can be exacerbated or accelerated by extreme high or low heat. As previously noted, high heat can result in expansion, softening and relaxation, while low temperatures will cause materials to contract and shrink dimensionally. Low temperatures will also make substrates brittle and rigid – and harder is not always better. In the same way that applications calling for strong, rigid materials must be able to withstand the changes that occur at high temperatures, an application that requires flexible substrates, i.e. gasketing with rubber O-rings, must be able to accommodate the physical and dimensional changes that occur under low temperatures.

2.2.3.3 EXTERNAL ENVIRONMENT AND HUMIDITY

SonerCdem/Getty

FIGURE 37

External weather conditions

When designing parts and components for external use, it is important to consider environmental factors other than temperature. Humidity and moisture can have a detrimental effect on many materials and joining methods. Vehicles produced in the automotive industry several decades ago were plagued by rust and corrosion issues in seams and body panels, as well as rivets and other mechanical joining methods. Beyond basic consideration of the substrate materials and the most suitable method of joining, protective coatings, paints and finishes can be applied to increase the durability and longevity of the components. Overall, the critical performance factors driving the development and use of coating technologies to protect exposed surfaces are (a) aesthetic characteristics, (b) corrosion protection, (c) mass production,

(d) cost and environmental requirements and (e) appearance and durability.(3) Although the relative importance of each of these factors is debatable, the perfection of any one at the expense of another could be unacceptable and uncover hidden flaws in the design or material selection. These are key points to note, particularly when selecting metals that are not known for long-term resistance to moisture and humidity, such as iron or steel, or when such materials are not pre-treated to achieve the necessary long-term performance, i.e. raw aluminium is known to corrode, while anodised finishes will offer longer lifespans without showing signs of degradation.

F38

FIGURE 38

Corrosion

F39

FIGURE 39

Rivets and other fasteners are subject to chemical attack or environmental conditions

Many engineering plastics are inherently resistant to moisture and humidity, with thermoset polymers often being selected over cheaper thermoplastics when high performance is required. Each application is different and, often, operating conditions and performance requirements must be balanced or prioritised to ensure that parts offer the desired or necessary features, even after extended ageing.

Moisture and humidity may not affect or degrade the chosen materials, but the behaviour of the materials when exposed to moisture needs to be observed – glass is permeable and will allow the transmission of moisture, whereas woods may swell and soften as they absorb water. All of these differing behaviour traits and characteristics of materials will impact the choice of joining method. Rivets and bolts may be used to fix non-permeable or moisture-resistant surfaces, but these fasteners in turn may be subject to attack by moisture, rendering the choice of exposed surface materials moot.

In addition to noting the hygroscopic or hydrophobic nature of materials and fasteners when exposed over their life cycles, relative humidity will also affect production and assembly processes. High relative humidity can cause condensation to form on surfaces, leading to flash rust/corrosion of some metals and reduced friction on parts where mechanical interference is required for fixing or securing mating surfaces. Regardless of the proposed or specified joining method, overall success demands an understanding of how environmental factors will impact the chosen materials and fasteners in the long-term, as well as during production.

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3) Nelson K. Akafuah, Sadegh Poozesh, Ahmad Salaimeh, Gabriela Patrick, Kevin Lawler, and Kozo Saito, *Evolution of the Automotive Body Coating Process—A Review*. Mechanical Engineering Faculty Publications. 25. 2016.

2.2.3.4 CHEMICAL RESISTANCE

Another factor affecting substrate materials, joining methods and joint durability is solvent and chemical exposure. There are many materials, compounds and solutions that can chemically attack a material, leading to both visual and structural changes of the substrate and the chosen joining method.

F40

FIGURE 40

Understanding chemical exposure of an assembly is critical for long term durability

F41

FIGURE 41

Stress corrosion of welded stainless steel

MadamLead/Getty

Corrosion is an attack on a material, most often metallic, that results from a chemical or electrochemical reaction with the surrounding media and environment.

Material damage and subsequent component failure due to corrosion can be eliminated by selecting the optimum material for a given application. The corrosiveness of a liquid on metals is mainly dependent on the liquid’s oxygen, chloride and/or sulphide content, temperature and pH. Chemical corrosion of a material can be combatted and counteracted at the design phase with the selection of appropriate materials, a suitable design for the product considering the operating environment, protective coatings, correct installation/maintenance and sufficient testing. Contact with corrosives can damage containers, equipment, installations and building components made from unsuitable materials. The stronger the corrosive and the higher the temperature, the greater the rate of metal corrosion. When acids attack metals, hydrogen gas is often given off. This is a flammable gas which can burn or explode if an ignition source is present. Common bases, such as sodium hydroxide and potassium hydroxide, can also attack metals like aluminium, zinc, galvanised metal and tin to produce hydrogen gas. It is important to review the relevant safety data sheet (SDS) for a particular corrosive and understand what metals or other materials, such as plastics or wood, it will attack.(4)

The resistance of polymers to corrosives is dependent on the structure of a given polymer. Some polymers, such as cellulose acetate, do not exhibit outstanding resistance to acids and alkalis. Most polymers are less brittle than more chemically resistant ceramics and are more resistant to corrosives than most metals. The rate of attack of polymer molecules by corrosives may be enhanced or hindered by the presence of neighbouring groups. Carbon-to-carbon bonds are not readily cleaved by acids, bases and corrosive materials, whereas carbon bonds with oxygen, sulphur or nitrogen, which are ionic and/or highly polar in nature,(5) are more readily cleaved.

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4) Canadian Centre for Occupational Health and Safety, 2008, Corrosive Materials – Hazards, www.ccohs.ca/oshanswers/chemicals/corrosive/corrosiv.html, 6th May 2021.

5) R. B. Seymour et al., *Structure – Property Relationships in Polymers* (New York: Plenum Press, 1984).

In a chemical attack, a reaction takes place on the molecular chain of the polymer or elastomer. Often such reactions will cause the chain to break or 'unzip'. When a plastic/elastomeric part experiences a chemical attack, the smaller segments of the molecular chain will have reduced entanglement; this lowers the material's tensile strength, tensile elongation and impact resistance, leading to a failure of the manufactured components.

Physical absorption does not involve a chemical reaction with the polymer chain; instead, the chemical is absorbed into the plastic, much like how water is absorbed into a sponge. Once inside, the chemical can cause changes in the weight, hardness and dimensions of a plastic part. In some cases, the chemical acts as a plasticiser, making the plastic softer and more flexible. In other cases, the chemical extracts a plasticiser that was part of the original formulation, causing the plastic or elastomer to become brittle.(6)

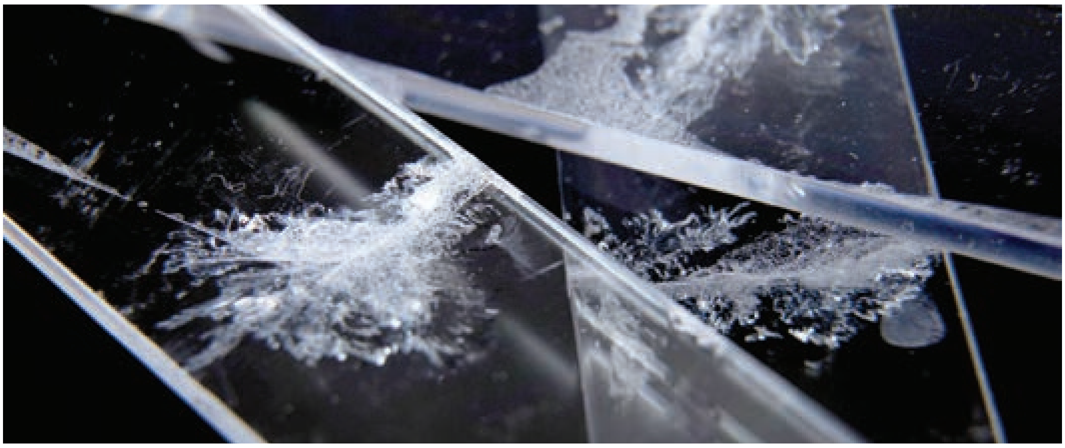

FIGURE 42

Stress cracking of plastic parts

The presence of internal and external stresses makes plastic parts more vulnerable to chemically induced failures. Internal stresses are introduced into a part during processing and fabrication. External stresses are the result of the mechanical loads applied to a plastic part. Environmental stress-cracking occurs when a chemical sufficiently weakens the plastic to allow internal and external stresses to initiate localised cracking, known as crazing.

Assessing the expected longevity of a plastic or elastomeric part requires knowing the manner of exposure to a chemical. Chemical reactions sometimes require considerable time before appreciable damage takes place. Wiping away incidental splashes, where possible, before they can be absorbed into the plastic can help extend the lifetime of a component. The more surface area that is exposed to a chemical, the likelier it will undergo a chemical attack.

Creating designs that limit the surface area exposed to chemicals can also help extend part life and reduce failures or unexpected downtime.

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6) Curbell Plastics, *Selecting Plastic Materials for Use in Chemical Environments*, www.curbellplastics.com/Research-Solutions/Resources/Articles/Plastic-Materials-in-Chemical-Environments#:~:text=In%20chemical%20attack%2C%20a%20reaction,chain%20will%20have%20reduced%20entanglement, 6th May 2021.

Typically, glass is considered a chemically resistant material. Glass is resistant to most acids but is highly susceptible to attack by alkaline materials. For applications that require operation in conditions where strong bases are expected, specialist grades of glass, such as borosilicate, should be specified.

The use of wood in chemical processing and for the storage of corrosive chemicals is well established, and wood is generally regarded to possess a high degree of resistance to degradation by numerous chemicals. Wood is most severely attacked by strong acidic and caustic solutions, representing extremes in pH values, and by powerful oxidising agents.(7) Different woods vary greatly in their resistance to chemical degradation, but overall, softwoods display more resistance than hardwoods.

Given the wide range of behaviours of common engineering materials when in contact with solvents/chemicals, it is critical to fully understand a material's capabilities and to know the range of environments and media to which a finished component may be exposed. Components and designs are expected to operate in numerous harsh environments, ranging from direct contact with fuels and lubricants to operating near radioactive substances and immersion in plant water and wastewater. Consideration must be given to the performance and changes in both the selected materials and the proposed joining method. A selected joining method will require a material (e.g. steel bolts or an epoxy adhesive) that performs the function of joining, securing or sealing a given number of surfaces, is resistant to the expected media and can withstand the loads and forces applied to it during operation.

TABLE 6

Chemical resistance of common substrates

	SUBSTRATES	WATER	ALCOHOLS	FUELS	OILS/ LUBRICANTS	ACIDS	ALKALIS
METAL	(Anodised) Aluminium	✓	✓	✓	✓	✓	✓
	(Stainless) Steel	✓	✓	✓	✓	✓	✓
PLASTIC	Standard Plastic	✓	⊖	⊖	✓	⊖	⊖
	Engineering Plastic	✓	✓	⊖	✓	⊖	⊖
	High Performance Plastic	✓	✓	✓	✓	✓	✓
	Rubber	✓	✖	✖	⊖	✖	✖
	Composites	✓	⊖	⊖	⊖	⊖	⊖
	Glass	✓	✓	✓	✓	✓	⊖
	Hardwood and Softwood	✓	⊖	⊖	✓	⊖	⊖

✓ Good Resistance ✖ Poor Resistance ⊖ Average Resistance

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7) A. Kass, F. Wangaard and H. A. Schroeder. *Chemical Degradation of Wood: The Relationship Between Strength Retention and Pentosan Content*, Wood and Fiber Science, Issue Number 1 / Spring 1970.

2.2.3.5 UV RESISTANCE AND STABILITY UNDER UV LIGHT

UV radiation, which consists of photons with high energy relative to visible light, can cause degradation in the form of physical and chemical changes in materials. UV radiation will affect susceptible materials that are intended for use and storage outdoors and are, thus, exposed to sunlight.

Metals, which are good conductors of electricity and heat, also interfere with electromagnetic radiation. Metals are almost entirely unaffected by UV radiation and can therefore be considered impervious to UV degradation.

FIGURE 43

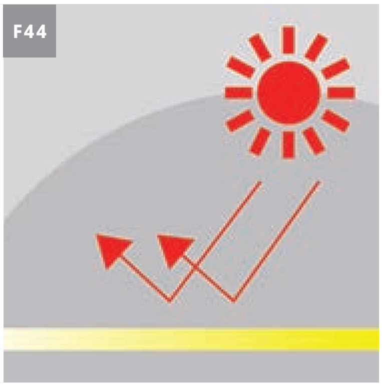
Plastic degraded by exposure to UV radiation

F43

FIGURE 44

UV radiation from sunlight

F44



Polymers and elastomers are almost always electrical insulators and poor conductors of heat. Since most polymers and elastomers consist of covalently bonded organic constituents, most are susceptible to UV damage. The most prevalent type of UV damage to polymers and elastomers is breaking long chains into shorter ones through the direct action of high-energy photons.

This process reduces the molecular weight of a polymer and almost always results in the degradation of physical properties, such as strength and ductility, and the degradation of aesthetic properties, such as colour and texture. Some familiar examples of UV-induced polymer degradation are the yellowing and chalking of PVC pipes, fading colours on signage and posters, and the chalking and embrittlement of insulation wires. Some polymers withstand UV exposure better than others. Polyolefins, such as PE, are often selected for external applications where UV radiation is expected. Fluoropolymers, like PTFE (Teflon) and FEP (Fluorinated ethylene propylene), demonstrate excellent UV resistance and are almost always used for wire insulation on UV lamps or in UV equipment.

In glass, the dominant mechanism of UV degradation in fused silica is related to impurities that are inevitably present in the glass. Freed electrons can form 'colour centres' and cause a reduction of UV transparency in the glass over time, called solarisation.(8) Typically, over regular design life expectancies, glass is resistant to UV and is utilised for its resistance and transparency.

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8) Chris Rockett, LightSources, Inc., *'UV Degradation Effects in Materials – An Elementary Overview,'* UVSolutions (2019), accessed May 7, 2021, uvsolutionsmag.com/articles/2019/uv-degradation-effects-in-materials-an-elementary-overview/.

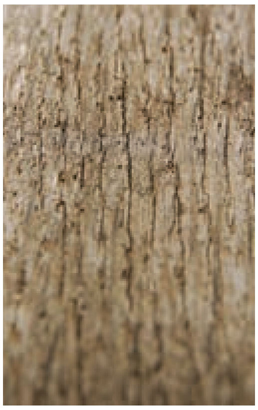

FIGURE 45

Sun-bleached/ UV degraded wood

Natural wood exposed to UV radiation undergoes rapid colour changes and breakdown of wood polymers in the surface layer. The combined effect of UV radiation and other environmental agents such as water and temperature, described as weathering, severely affects the life of timber in external applications. The colour stability of natural wood to light exposure is also an important issue from an aesthetic viewpoint. To ensure long life, wood substrates are usually coated with various decorative and protective finishes, such as paints, transparent finishes and varnishes.(9)

The simplest method for preventing the UV degradation of an object is to protect it with a barrier that is impenetrable to UV radiation, known as shading or shielding. When a physical shade is not possible, the alternative is to apply a coating or paint that absorbs or reflects UV.

Designs that minimise UV exposure or rely solely on a UV-resistant material for all exposed surfaces will ensure the performance of the selected material and joining method under long-term UV exposure. Appropriate material selection will also prevent degradation and reduce the risk of embrittlement/ softening (depending on the substrate in question) and negative aesthetic impact, which may result in premature failure or the rejection of products and manufactured goods.

2.2.4 EXTERNAL ACTING FORCES

Another important consideration when selecting materials and joining methods is factors outside of the system and the design parameters for the finished components. Cyclic stresses, particularly slow ones, are much more damaging to materials and joined assemblies than steady stress. The materials and joining method(s) selected for a particular application must resist these loads and stresses, even after sustained exposure to environmental factors encountered during the life of the assembly. Externally acting forces and applied loads can lead to fatigue, deformation, weakening and degradation of parts and materials. These effects are amplified or highlighted if an unsuitable method of joining is selected, even more so if an inconsistent joining method combines with a questionable material selection, which has been known to occur in the manufacture of low-cost consumable items.

THE MAIN LOADINGS OF BONDED JOINTS

- Tensile and compressive stresses produced by out-of-plane tensile or compressive loads
- Shear stresses produced by tensile, torsional or pure shear loads imposed on substrates
- Cleavage loads produced by out-of-plane tensile loads acting on stiff and thick substrates at the ends of the joints
- Peel loads produced by out-of-plane loads acting on thin substrates.

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9) Jayashree Salla, Krishna K. Pandey, Kavyashree Srinivas, 'Improvement of UV resistance of wood surfaces by using ZnO nanoparticles,' *Polymer Degradation and Stability,* 97, no. 4 (2012).

These loads will also affect assemblies joined using other methods and processes; however, many traditional ways of joining materials will be subject to other forces that result from the load types. For example, a bolted or riveted assembly will have stress concentrations around the holes or areas of less material. Under loads exceeding the design capabilities, or in high-impact situations, such as crashes, failure of the material and joint will occur at the point(s) of highest stress, i.e. around the rivets or bolt holes. By comparison, a bonded joint will spread and accommodate continuous and shock loads more evenly.

FIGURE 46

Stress distribution in riveted assemblies

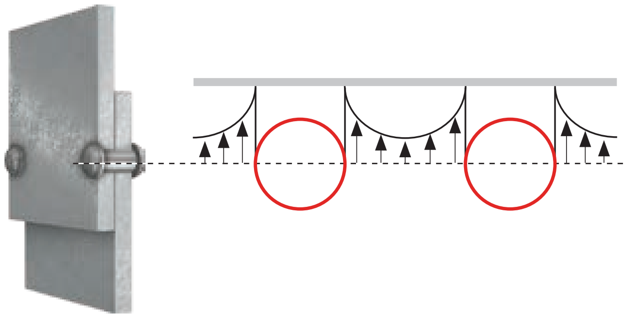
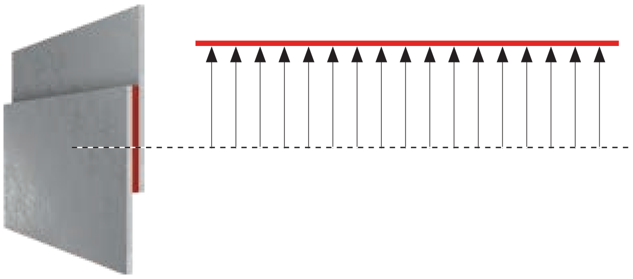


FIGURE 47

Stress distribution in bonded assemblies



While later sections focus on joint design and common failure modes of materials and joined assemblies, this section discusses a few factors and loads that may affect a material and joining method. Beyond the environmental factors addressed and the expected loads that are foreseen in the early design phases of a product, there are several additional factors to consider:

- Pressure
- Vibration
- Variable loading through substrates or from peripheral features
- Impact and shock

2.2.4.1 PRESSURE

FIGURE 48

Pressure

Pressure is often a known acting force and is usually considered when designing and manufacturing components. A gas canister is a familiar standard pressure vessel used to contain compressed gases. They are designed and manufactured with a high safety factor to prevent failures, reduce the risk of injury and resist changes in pressure. These changes may be brought on by many factors, including temperature changes, causing the contained media to compress or expand and surface deformities from impact (dropping of the canister), which may reduce the internal area that the same volume of gas may occupy.

Changes in pressure can arise from within a part, act on the external surface of it, or both. These changes may be brought on by numerous factors and combinations of varied or incremental adjustments to the parts themselves, the environment in which the parts operate or surrounding components and features.

Atmospheric pressure changes are usually inconsequential, unless travelling to or from a great height. This cannot be said for subsea applications, where small changes in depth can result in significant increases in the compressive force acting upon an assembly due to the increased pressure from the weight of the water above. Temperature changes can also increase or decrease the pressure acting on a component. These variations are most apparent when dissimilar materials are combined and joined due to their variable coefficient of thermal expansion rates. Pressure can also increase at specific locations over time where localised or distant material or joint failures become apparent but do not lead to an assembly's operational or complete failure. When selecting a joining method, it is vital to understand how the stress applied by pressure variations is spread and accommodated to ensure parts meet their design's life expectancy.

2.2.4.2 VIBRATION

Tattoboo/Shutterstock

FIGURE 49

Vibration

Vibration is a mechanical phenomenon in which oscillations occur around an equilibrium point. Vibration can be desirable (loudspeaker cones are an example), but in many cases, it is undesirable and wastes energy, creates unwanted sound and causes mating faces to move against or away from one another. Vibration and shock increase the relative movement of parts and materials joined using most traditional methods, causing a loss of clamping force and, ultimately, machine or component failure. Vibration can severely impact the performance and durability of many joining methods. Repeated or continuous exposure can also weaken substrate materials, mainly where localised stresses and material deficiencies are present due to the selected joining method.

Extreme vibration and movement can highlight the harmonic resonance of a component or structure, as seen during the Tacoma Narrows Bridge incident. The Tacoma Narrows Bridge was built in Washington during the 1930s. It was designed to be the most flexible bridge ever constructed. While the design exceeded the calculated ratios of length, depth and width, the aerodynamic forces in play during strong winds were not considered.

FIGURE 50

Vibration and induced harmonic resonance – Tacoma Bridge

july7th/Getty

On 7th November 1940, high winds buffeted the area and the bridge swayed considerably. Concrete dropped from the road surface during the first failure, and later, a 183 m (600 ft) section of the bridge broke free as the bridge was wildly tossed back and forth. At its peak, the elevation of one side of the bridge was 8.5 m (28 ft) above that of the other side. Despite using structural carbon steel for the bridge towers, the violent movement caused the bridge to collapse. Subsequent investigation and testing revealed that the bridge was vulnerable to vibrations generated by wind. When exposed to strong winds from a particular direction, the frequency oscillations built up to such an extent that collapse was inevitable.

FIGURE 51

Automotive noise reduction/ anti-flutter

Vibration must also be accounted for in assemblies with joined panels and significant gaps or voids between the mating surfaces. Noise and vibration are critical considerations in the automotive industry. Often door and body panels are fastened to each other and the chassis using structural methods such as welding, riveting or bonding. However, efficiency is a considerable driver in such industries, with great importance placed on weight saving. Therefore, lightweight materials are used to craft large surfaces from thin bodies of material, increasing the potential for movement, bowing and vibrating of large surface area panels. Car doors are a typical example where vibration causes unwanted noise and fatigue; filling the cavities and voids with sound and vibration dampening material helps overcome such issues.

2.2.4.3 VARIABLE LOADING

FIGURES 52 & 53

Examples of variable loading through substrates

F52

Inzyx/Getty

F53

Art Wager/Getty

Variable loading through substrate materials usually happens because of design inefficiencies and oversights, or where components or features are supported by load-bearing structures, such as pipe and bridge supports. In such scenarios, it is not only the static weight of the feature that is being supported and absorbed but also the dynamic loads applied to these components. All the factors previously mentioned can contribute to a change in the properties, performance and dimensions of a material or part. Usually, these dynamic and static loads that will apply a force to the underlying or surrounding substrate material are expected, i.e. moving traffic on a bridge transferring a load to the supports or vibration transferred through the mixing bowl of a food processor to the base of the unit. It is imperative to anticipate the direct and indirect loads applied to a substrate or component, whether they are expected or possible, i.e. in the event of a crash or impact. It is not only the material that must be assessed to ensure suitability; the joining method must also be thoroughly reviewed and tested to ensure that it can accommodate all potential variables encountered during its lifetime.

2.2.4.4 IMPACT AND SHOCK

FIGURE 54

Impact

CHRISsadowski/Getty

Impact and shock are externally acting forces that designers often account for, but knowing the location, direction and magnitude of the impact is nearly impossible to predict. Many industries, notably the automotive, aerospace and rail industries, conduct extensive modelling and failure modes and effects analysis (FMEA) calculations. In applications where there is a greater risk to life in the event of an impact or crash, these analyses and tests ensure that the performance of a product or vehicle is fit for its purpose and is safe. Often, it is not how resistant to shock or impact a material is that will allow its selection and inclusion within a design, but how it will transfer the load through itself and deform with or against surrounding materials or components. Plastic and aluminium body panels are selected for their lightweight and processing properties but also for their ability to deform during a crash and transfer the shock loading through various planes to surrounding, stronger components, such as vehicle crumple zones. It is the behaviour of a material under such conditions that may lead to its selection. The same is true for the method of joining parts and securing them together. A riveted assembly has numerous localised stresses within the materials due to the joining method and process. Usually, parts are torn along such seams when great shock and impact loads are applied. A clipped assembly may perform similarly, where the clip fasteners also deform due to impact and allow the previously joined substrates to move away from each other freely. This results in an uncontrollable deforming of parts that may not allow the impact to be channelled in the desired direction, causing further damage.

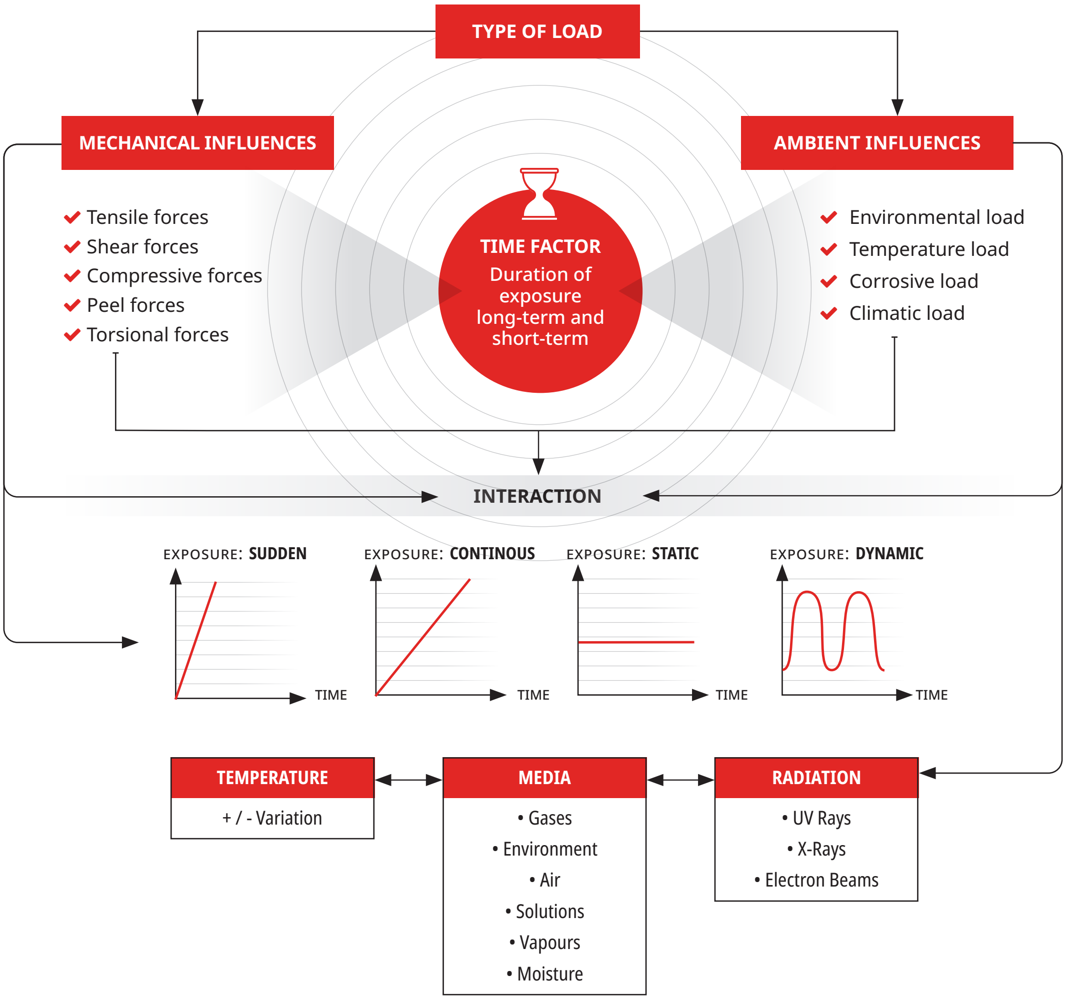


FIGURE 55

Loads to which materials and assemblies are exposed

2.2.5 DESIGN AND MANUFACTURING PARAMETERS

Design parameters and the manufacturing requirements of a product influence the selection of a joining method. Various manufacturing parameters must be considered when selecting joining or assembly methods for production.

2.2.5.1 MACHINING ACCURACY

The machining accuracy of any component is affected by many elements, particularly two core factors:

1. Surface finish **2. Tolerance**

Grinding, honing, buffing, polishing, lapping and burnishing are common methods used to achieve the desired surface finish. Surface finish (Ra) is the average of the maximum (peaks) and minimum (valleys) values of the roughness profile (height) for the given material. A tighter or narrower range for these maximum and minimum values will result in a more refined surface finish and a smoother topology.

Changing the designated surface finish of a material from 3.2 µm to 0.8 µm (125 µin to 32 µin), for example, can significantly increase associated machining costs. The key reasons behind this increase are the manufacturing process changes and the number of machine passes required to achieve a finer surface finish, which increase the time spent producing a single component.

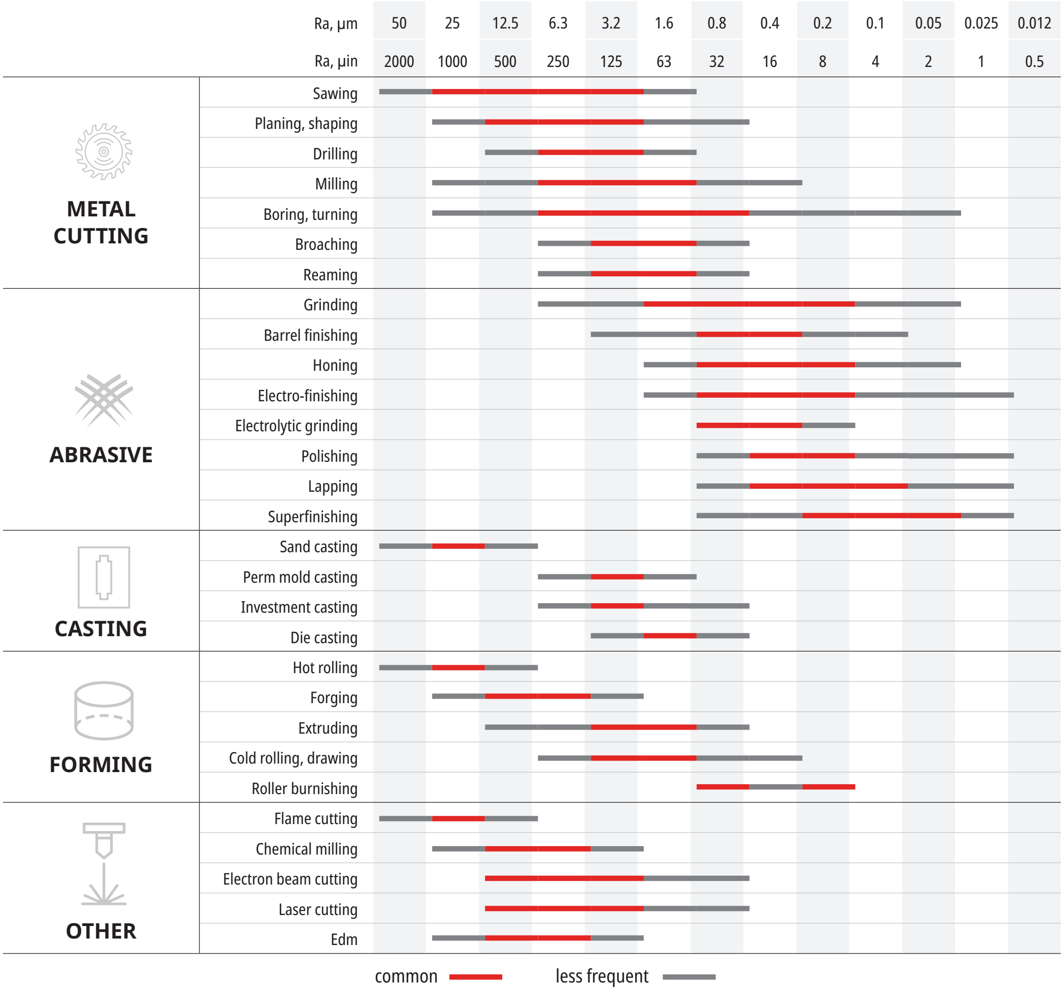


FIGURE 56

The surface finish is highly dependent on the manufacturing process being used

A designer may opt for an appropriate yet rough surface finish and high tolerance to realise the lowest machining costs. Other applications may allow for the combination of a rough or smooth surface finish with either tight or loose tolerances, depending on whether cost or performance is most critical. The surface finish and tolerances may affect the selection of an appropriate joining method. If the tolerances are tight, one can easily select a 'Shrink Fit' or 'Bonded Press Fit' to join a shaft and bearing assembly, for example.

2.2.5.2 COSMETIC APPEARANCE

The aesthetics of a product can be critical to ensuring that end users perceive the quality of a product to be high, so a designer or manufacturer needs to use a joining method that can provide the desired aesthetics. Figures 57 and 58 show some examples.

F57

FIGURE 57

Aesthetics of a riveted assembly are remarkably different from a bonded assembly

2.2.5.3 AUTOMATION VS MANUAL ASSEMBLY

Determining the most suitable production process is based on multiple parameters. The daily production rate is generally a good starting point.

Joining methods should be compatible with automation machines and robots to keep up with the production demands. For example, welding and adhesive bonding can be automated simultaneously on the same production line, while assembling fasteners and adhesive bonding cannot be easily automated.

F58

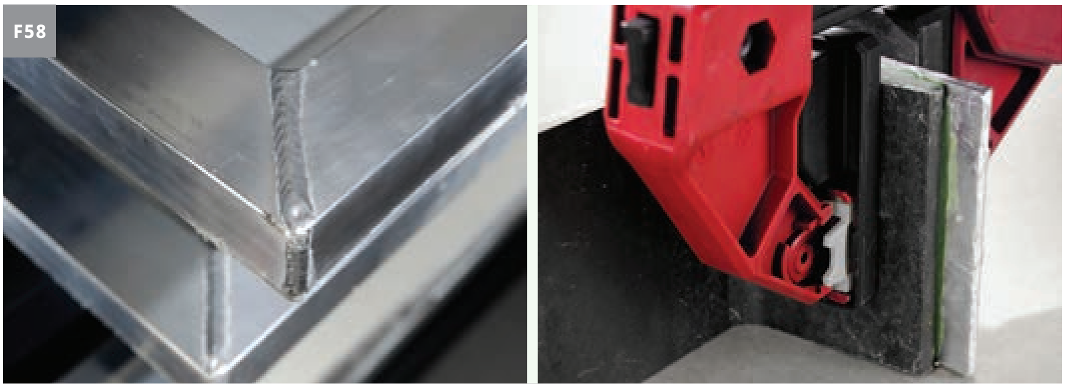


FIGURE 58

Closeup of weld line on aluminium metal parts and adhesive bonded joint


F59

FIGURE 59

Adhesive bonding can be easily automated on the production line


F60

FIGURE 60

Example of robots being used for welding in car manufacturing

2.2.5.4 SEALING OF THE JOINT OR ASSEMBLY

For an assembly to perform effectively, sealing can be critical. Sealing means keeping the environment or media on one side of an assembly and out of the joint. This is important in some situations, as atmospheric moisture can lead to water ingress between joining surfaces and induce corrosion. Keeping fluids inside or outside of an assembly can be a critical requirement for an application, e.g. water storage tanks, filter housings, shipping containers, rail carriages and medical devices. Joining methods such as welding, bonding and brazing are preferred where sealing is required. Fasteners and rivets can be selected if sealing is not a priority.


F61

FIGURE 61

Windscreen bonding and sealing

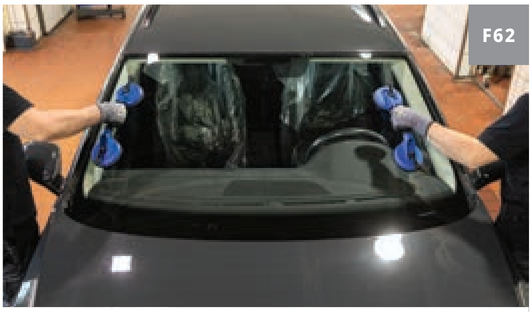

F62

FIGURE 62

Direct glazing with polyurethane adhesive is used to bond and seal windscreens in many vehicle types


F63

FIGURE 63

Rivets are not designed for sealing

Douglas Sacha /Getty

2.2.5.5 EXPECTED LIFE OF THE ASSEMBLY

The following are two important considerations in determining the expected life of an assembly:

1. Does the assembly require corrosion protection, or will the parts corrode by design?

2. Is dismantling required for maintenance of the assembly, and if yes, how frequently?

Joining method selection depends on the requirements of an assembly. Rivets or bolts cannot seal against the environment. Welding joints can seal; however, they become a starting point of corrosion in many cases, often due to the flux used during welding processes. Hem joints bonded with adhesives are the preferred choice of assembly design (commonly used in the automotive industry) to prevent corrosion and maximise the lifetime of the assembly. Bonded substrates will seal; however, dismantling bonded parts can be challenging.

FIGURE 64

Hem joints are considered reliable ways to seal against environment for assemblies (e.g. car door) to ensure long life of assembly

SECTION THREE

THE EVOLUTION OF JOINING

AS DISCUSSED IN PREVIOUS SECTIONS, BONDING HAS BEEN AN ACCEPTED SOLUTION FOR JOINING MATERIALS FOR THOUSANDS OF YEARS. However, it is only in the last century that adhesives have entered their ‘golden age’. The pace of bonding technology development during the 20th century facilitated many technological advancements that would not be possible, or nearly as affordable, without the use of highly specialised adhesives. The following sections address many of the advantages and advancements that adhesives facilitate. These include reduced weight, increased efficiency, incorporation of new substrates, improved aesthetics and improved strength-to-weight ratios. The specifics of load distribution, acting forces on an assembly, environmental factors and substrate properties are addressed in other sections of this book.

3.1 EVOLUTION OF BONDING

3.1.1 INCORPORATING NEW SUBSTANCES

Adhesive bonding is an efficient, economical and durable method for assembling dissimilar materials. It is highly versatile and capable of joining almost all types of materials to themselves and each other. Other joining methods and processes, such as welding and riveting, are limited by material characteristics, joint geometries and application requirements. Bonding is used for many applications, including joining films, sheets, fabrics, sandwich panels, honeycomb cores, sandpaper, cardboard boxes and flocked wallpaper.

An adhesive can compensate for joint tolerance by filling gaps and surface variations, allowing increased flexibility and load transmission. An adhesively bonded joint can also seal against liquids (preventing corrosion of metals) and gases. Many adhesives are based on organic polymers, which are non-conductive and can provide electrical insulation. If this is not desired, metal powder (usually silver) is added to an adhesive to increase its electrical conductivity. These adhesives are commonly used in microelectronics for the transmission of currents. Some adhesives are specially modified for heat transfer and have high or low thermal conductivity.(10)

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10) Brune, Kai & Dieckhoff, Stefan & Fricke, Holger & Groß, Andreas & Haag, Katharina & Hartwig, Andreas & Cavalcanti, Welchy & Mayer, Bernd & Noeske, P.-L & Wilken, Ralph. (2020). Circular Economy and Adhesive Bonding Technology Study by the Fraunhofer Institute for Manufacturing Technology and Advanced Materials IFAM (B. Mayer, A. Groß; eds.). 10.24406/ifam-n-603186.

These properties of adhesives allow dissimilar materials to be joined and combined in endless applications, offering increased design freedom and often enabling fuel and energy savings both in production and during operation.

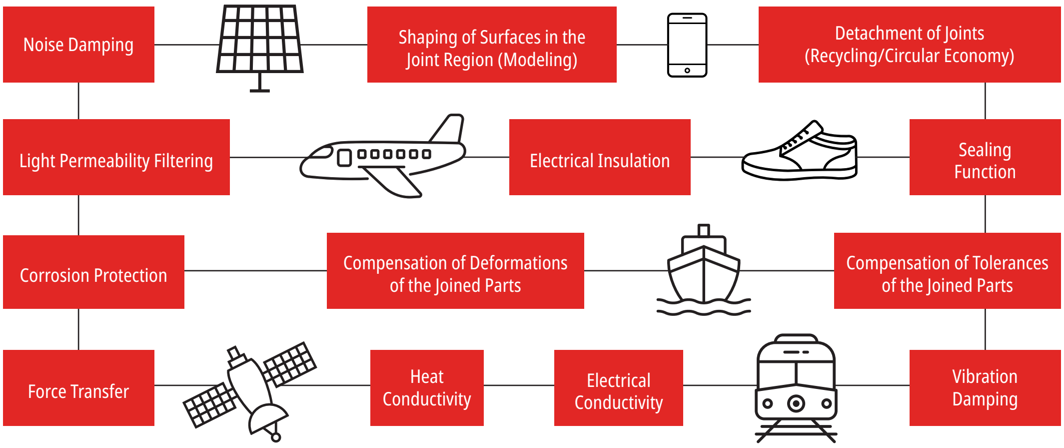

FIGURE 65

Possible functions of an adhesive in an adhesively bonded joint

3.1.2 WEIGHT CONSIDERATIONS AND STRENGTH IMPROVEMENTS

Reducing the overall weight of an assembly, or lightweighting, involves using advanced materials and engineering methods to enable structural elements to deliver the same or enhanced technical performance while using less material. The concept has been extensively explored and utilised in many industries, from automotive applications to fashion and packaging, and it offers significant potential performance and efficiency gains.

Lightweight materials have developed into a crucial success factor for resource efficiency in numerous industries as weight reduction leads to lower fuel or energy consumption in almost all applications. In the aerospace industry, multi-substrate bonding solutions provide up to a 30% weight reduction compared to components made solely of steel or aluminium. Therefore, durable and robust bonds, optimised curing speeds and the possibility of bonding various materials are invaluable in such industries. Matrix resins allow for the production of exceptionally lightweight fibre-reinforced composite structural components; these adhesives are used to bind fibre matrices under heat and pressure to form an extremely robust yet light finished material.

The automotive industry uses the most lightweight materials, mainly out of necessity, as manufacturers must respond to increasingly strict emission regulations. For electrically powered cars, efficient but heavy batteries must be used in lightweight cars to maximise the potential range and satisfy consumers who are used to the convenience of fossil fuel-powered vehicles. Modern adhesives and composite materials reduce the weight of cars by up to 15% versus common all-metal (steel or aluminium) components. An example is localised reinforcement within pillars and designed gaps using high-performance structural foams.

A hybrid vehicle structure consists of a fibre-reinforced frame or carrier – e.g. injection moulded glass-filled PA resin – and structural foam injected at predefined sections. The foam expands during a heat curing process (used for curing chassis-protecting e-coat systems) and creates a stiff connection between the hybrid structure and the body-in-white unit. Compared to all-metal structures, the design freedom and efficient processing offered by fibre reinforced plastics (FRP) and foam materials facilitate the adaptation of each structure to the required geometry, with locally stiffening foam ribs added precisely where needed. The structural foam used in such hybrid designs is an epoxy-based material that delivers high strength and stiffness at a low weight-to-volume ratio.

FIGURE 66

Potential for lightweighting with hybrid designs using high-performance structural foam in body and closure parts

Lightweighting is also essential in the aerospace and shipbuilding industries. In heavy seas or turbulent weather conditions, ships and aeroplanes are exposed to tremendous forces and violent impacts. Therefore, it is critical to correctly specify a rigid or elastic adhesive for a given application. Unlike mechanical joints, such as rivets or screws, adhesive bonding can accommodate variable loading and prevent components or surfaces from separating due to the two-dimensional transmission of force. In addition, the adhesive may provide a vibration-damping effect, which in turn increases passenger comfort. For example, windows are no longer made of glass, but PC; these plastic windows are bonded in place using strong and flexible adhesives.

Over the lifetime of a ship or aircraft, the long-term stability of a multi-material lightweight construction achieved using adhesive bonding technologies dramatically reduces its fuel consumption and carbon dioxide (CO_2) footprint. As previously discussed, adhesives can also improve manufacturing efficiency, resulting in a more sustainable and eco-friendly overall process.

Adhesive bonding strengthens the overall assembly: bonding offers several advantages over mechanical joining methods, such as welding, rivets, nuts and bolts, and crimps. Mechanically joined assemblies are usually expensive due to the following factors:

- Higher component costs (nuts and bolts, rivets, equipment)
- Additional processes (drilling holes for nuts and thread cutting)
- Need for skilled labour (welder, grinder)
- Secondary finishing operations (grinding, polishing)

Nevertheless, adhesive bonds can join dissimilar substrates with differing coefficients of thermal expansion, are invisible in an assembly and can bond and seal in one step. The most important advantage of adhesive bonds is that they can evenly distribute the stress over a broad area rather than concentrating it in a small area, thus reducing stresses on the joint. The structural stress is concentrated around the rivets in the riveted assembly, even though a greater contact area between the parts is available. However, the stress is distributed over the entire contact area between the two parts in a bonded assembly (this concept is covered in detail in Section 4). In many cases, an assembly joined using traditional methods must be strengthened around the joint to avoid failure during the operation.

3.1.3 SUSTAINABILITY

Sustainable adhesives are divided into five categories:

1	Repulpable Adhesives:	These adhesives are dissolved in water during the paper-repulping process, eliminating residues or films left behind by non-repulpable products. Such adhesives are typically used to produce cardboard boxes, envelopes and other paper product applications.
2	Renewable Adhesives:	These adhesives use raw materials from renewable sources, such as plants and beeswax, rather than petroleum sources. In addition to the decreased carbon footprint, they enhance the sustainability of many applications.
3	Recyclable Adhesives:	Recyclable adhesives are often used in automotive applications and for bonding glass, aluminium and steel, for example. They are fully compatible with the bonded substrates and can be melted down without yielding any adhesive residue when the product reaches its end of life.
4	Biodegradable Adhesives:	These adhesives are designed to be degraded by bacteria and other living organisms. They produce water, CO_2 and other naturally occurring materials, depending on the environmental conditions. These adhesives are generally produced using naturally sourced or renewable raw materials.
5	Compostable Adhesives:	These adhesives are a subset of biodegradable adhesives. However, unlike biodegradable adhesives, these adhesives can be broken down within a compost pile and do not leave behind any harmful residues. The resulting compost can be used to fertilise the soil and grow crops.

3.1.4 NOISE, VIBRATION AND HARSHNESS (NVH)

While the term NVH is common in automotive manufacturing, unwanted NVH is prevalent in many other industries as well. Using adhesives over traditional joining methods contributes to reducing the noise generated by motors in vehicles, ships, aircraft and industrial machinery, allowing for silent operation of home appliances, such as dishwashers and refrigerators, or reducing vibration and associated rattling within air conditioning systems. Such reductions to ambient noise are becoming more routine, with many new designs using adhesives and sealants to achieve these operating characteristics. NVH products are typically designed for use within vehicles or for adhering to substrates used in automotive manufacturing (steel, aluminium, composites, etc.). These principles apply to the manufacture and operation of all appliances within any sector where there is a desire to minimise noise.

Some adhesives are designed to address NVH challenges, rather than physically blocking sound waves and generally behaving as an insulator. They are naturally viscoelastic and dampen sound by absorbing sound energy. For example, structural adhesives cure rigid materials and create solid connections that bond individual pieces or components to each other or a structure. In such instances, vibrations produce less sound energy, as they cannot move the bonded parts separately from one another; this reduces rattling noises (noise and vibration) and can extend the lifetime of a product.

The ability to accommodate or mitigate noise and vibration is essential when consistent impacts or shaking are expected during the operation of an assembly. Threadlockers also contribute to overall NVH performance by bonding threaded fasteners and resisting vibrational loosening and corrosion. Washing machines, dryers and other appliances subjected to high-frequency vibrations are good examples of where threadlocking adhesives help to augment the NVH performance of structural or gap-filling adhesives. Using rigid and elastic adhesives for strong connections or void filling, as appropriate, will contribute to reducing the overall noise generated, potential vibration and degrading effects of these harsh impacts.

3.1.5 PROMINENT INDUSTRIES AND APPLICATIONS

The transportation sector includes industries that have benefited from the advantages that adhesives offer for the longest time. When the first adhesive factories opened in Europe around 1700, it was quickly found that bonding materials could be beneficial in transportation applications. There were drawbacks to the adhesives made at this time, which were animal-based. These adhesives were not resistant to heat and water, making them only usable in areas on vehicles, such as wagons, carriages and trains, that were not exposed to hot and wet conditions.

In 1911, when automobiles and carriages shared the streets, *Carriage Monthly* magazine wrote about a new ‘waterproof glue’. When combined with formaldehyde, this animal-based glue could be applied cold and survive in wet environments. General-use automotive bonding adhesives were finally possible because of this innovation.(11)

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11) *‘Carriage Bodies and Parts,’* The Carriage Monthly, April 1911, p. 20.

3.1.6 AUTOMOTIVE INDUSTRY

The automotive industry is a significant driver in using adhesive technology. Many adhesive technologies are used in both the production and repair of modern vehicles. Adhesives make it possible to combine all types of diverse materials with strength, stiffness, corrosion resistance and, in many cases, a simpler manufacturing process. The windscreen of a vehicle is bonded in place instead of being squeezed into a rubber profile, as it was before. This not only offers sealing capabilities but also adds stiffness to the car body. Thinner and lighter glass can be used, thus decreasing the overall weight of the vehicle. Using adhesives to bond the windscreen increases safety by keeping passengers inside the car, acting as a backboard for the airbags and preventing the roof from being crushed in a crash scenario.

FIGURE 67

Vehicle undergoing crash testing, demonstrating the importance and performance of bonded windscreens

The successful use of bonding windscreens led to the use of adhesives in the body structure to add stiffness, reduce welds and provide sealed seams for extra corrosion protection and to prevent fluids entering the interior of the car (moisture, rain and exhaust gases). Bonded constructions offer more even energy absorption in the case of a crash than a spot-welded construction. Adhesives are used to reinforce pillars, as shown in Figure 68. The adhesives add stiffness without using a thicker metal, thus reducing the overall weight of the vehicle.

FIGURE 68

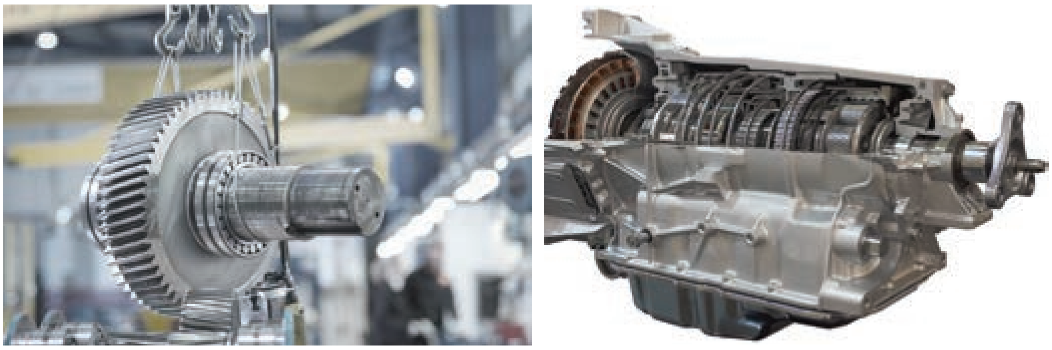
Three differently constructed crash elements: The one to the left is made of 0.8 mm thick metal and is reinforced with structural epoxy foam. It has a total weight of approx. 1.2 kg. The element in the middle has a wall thickness of 1.5 mm and is not filled. It weighs approx. 1.2 kg. The one to the right has a wall thickness of 0.8 mm, is unfilled and weighs approx. 0.6 kg

Other exterior applications for adhesives include roofs made of different materials, such as metals, glass or fibre-reinforced plastics bonded in place, mirrors, lamps, bumpers, spoilers and door flanges. Inside the vehicle, adhesives are ideal for laminating and bonding all interior components, including door panels, displays, dashboards, headliners, cockpit and instrument panels, and seat trims.

The powertrain of a car also contains many adhesive applications for sealing against different liquids and bonding within the engine, transmission, differential and driveshaft. For example, anaerobic retaining compounds are used to replace or improve traditional splines, press and shrink fits; they add strength, improve reliability and reduce the risk of fretting, contact corrosion and rust. Retaining compounds will also reduce the costly machining required to achieve complicated designs and narrow tolerances required for traditional methods. In hybrid and electric vehicles, the propulsion system includes the battery, electric drive system and control electronics. Adhesives are commonly used for sealing, encapsulation and heat transfer in these systems.

FIGURE 69

A producer of gearboxes for trucks switched from laser welding in combination with a shrink fit joint to a high-strength retainer due to fatigue issues



3.1.7 AEROSPACE INDUSTRY

At the beginning of the aerospace industry development, when aeroplanes were made mainly of wood and fabric, adhesives were used to join the components. When metals, primarily aluminium, became the default structural material used, mechanical fasteners were commonly used to assemble aircraft. Mechanical fasteners will always have a place in manufacturing assemblies, but adhesives offer many advantages. For example, much lighter bonded components are produced when opting to use adhesives over fasteners.

The aerospace industry's interest in the weight-saving properties of adhesives was renewed when it faced demand for lower fuel consumption, improved performance and more cost-effective production. The use of adhesives makes it possible to use high-strength, lightweight alloys whose properties are negatively affected when welded or riveted.

Adhesives also make it easier to use newly developed, high-tech substrates that offer unique properties, such as different polymer-based materials. Applications for bonding technology are also found in space exploration, where the ceramic tiles used to protect space shuttles against overheating when they re-enter the Earth's atmosphere are bonded to the shuttle's outer metal skin using heat-resistant adhesives.

3.1.8 RECREATIONAL VEHICLES

Recreational vehicles, including trailer caravans, should be robust and lightweight. Adhesives are used to produce the laminated (sandwich) elements for the caravan construction. Historically, the standard method for joining the laminate elements was to fasten them together mechanically and seal the joints with a non-curing sealant. Some recreational vehicle manufacturers have eliminated up to 90% of the screws used in their vehicles by using adhesives.

Henkel partnered with Elddis, a UK-based RV (caravans, motorhomes and van conversion) manufacturer, to prove this adhesive concept. A caravan was manufactured using the existing design, and the screws were replaced with a structural polyurethane (PU) adhesive and an elastic-modified silane adhesive, as appropriate. This bonded caravan was then heavily tested without breaking or showing signs of fatigue. The joint design was then optimised for use with adhesives for both strength and water tightness. This new design increased the bond area of the frame by 63%, making the structure lighter and ten times stronger than the precursor.

FIGURE 70

Recreational vehicles can be lightweighted through bonding

Using adhesives instead of mechanical fasteners reduces the need for stiffeners and offers the freedom to choose and combine a broad range of materials to create new designs. Liquid ingress is a recurring issue in the recreational vehicle industry; eliminating approximately 800 screws eliminates as many potential leak paths as possible, thus reducing warranty claims. In this example, it allowed the vehicle manufacturer to double the bodyshell warranty time for the bonded construction compared to the original design which used screws and mechanical fasteners.

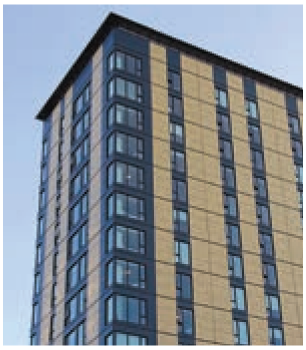
3.1.9 CONSTRUCTION

In modern buildings, adhesives are used almost everywhere because of their ability to combine different materials and offer fully sealed joints. They can be used for applications such as carpet laying, wallpapering, ceramic tiling, lamination of wood panels, bonding and sealing of ventilation and in water and heating systems. Adhesives also play an essential role in the manufacture of windows and doors. Specifically, fire doors use flame retardant adhesives that have passed severe testing.

Mass timber is a structural load-bearing element made from solid lumber glued together to form columns, beams and large format panels. Unlike traditional materials, such as concrete or steel, mass timber is renewable. Mass timber is earthquake resistant, difficult to burn and sequesters (stores) CO_2. Mass timber can be used to construct virtually anything, including high-rise buildings, multifamily homes, office buildings, factories and warehouses. It is lighter than concrete or steel, so it produces less carbon during transportation. According to industry studies, there is also an emotional benefit: People feel calmer and more productive in wooden buildings than in concrete or steel structures.

FIGURE 71

The mass timber Brock Commons building at the University of British Columbia



BrendanHunter/Getty

An impressive example of ongoing development in engineered timber construction is Brock Commons, the 18-story dormitory block at the University of British Columbia (UBC) in Vancouver, Canada. The building is 53 metres high, with accommodations for 404 students. During the construction period of just 66 days, 1,302 glued and laminated timber supports and 464 cross-laminated beams were joined together around two staircases and elevator shafts of concrete to form the load-bearing structure. Using an engineered timber solution allowed the above benefits to be realised and reduced the construction time.

3.1.10 PAPER

The paper industry uses several types of adhesives for many applications in various end products. Paper food packaging is bonded with adhesives approved for incidental food contact, such as takeaway beverage cups and paper straws. Paper straws are designed and manufactured to withstand immersion in liquid for one hour or more; this requires the adhesive and paper substrate to remain intact while submerged. After use, the paper material needs to be biodegradable to allow for proper decomposition. Paper degrades faster than plastic, with a reduced impact on the environment.

Adhesives are also used to produce bags, corrugated boards and envelopes. In the hygiene sector, adhesives are used in products for adult incontinence, baby diapers, tissues and towels. In a toilet paper roll, there are four unique applications for adhesives. The first is a core winding adhesive used to produce the cardboard roll. A laminating adhesive bonds the two to four plies of the toilet paper, giving the desired softness. Paper is bonded to the roll with another adhesive called a pick-up adhesive. Finally, the tail sealing adhesive completes the toilet roll. Each of these adhesive types comes in various grades to fulfil the end customer’s expectations and satisfy each production site’s needs. They must all also comply with the strict regulatory requirements of the relevant industry.

3.1.11 MEDICAL APPLICATIONS

Flexible tubes, needles and hubs are among the components in the medical device industry that require the flexibility provided by adhesives to join dissimilar substrates. Applications vary from bonding stainless steel cannulas into plastic hubs and adhering elastomeric balloons or plastic connectors to catheter tubes to assembling blood filters and reservoirs.

All of these different applications have some similar requirements and are typically produced in very high volumes. They require an adhesive that provides handling strength within seconds so that quality control can be done immediately on the production line. Often there is a need for fluorescence in the adhesive product so it can be detected to ensure correct and sufficient application. Most adhesives developed for the medical device industry are biocompatibility tested (ISO 10993) to meet the requirements and standards for the end product before launching into the market; this simplifies the certification process for the device manufacturer.

A selected adhesive for each application should also withstand the various sterilisation methods used for the end product. Special adhesives are even used for skin sutures. The use of adhesives allows incisions to be closed three times faster than with regular stitches, and they form a protective barrier against infection-causing bacteria. They are also gentler to the skin than stitches and eliminate the need for bandages. As the wound heals, the adhesive disappears without further intervention.

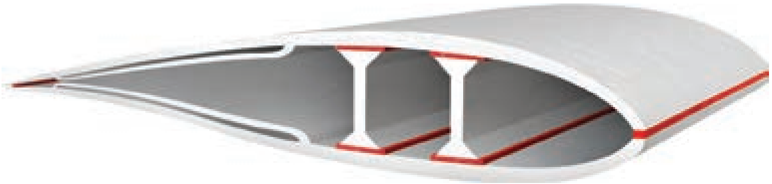
3.1.12 RENEWABLE ENERGY

Wind power has developed and evolved in recent years, mainly because of the increased use of adhesives to construct wind turbines. Wind turbines were previously made of galvanised steel, but aluminium and composite materials are now used for their lightweight properties. This material change also reduces the risk of corrosion. Wind turbines can be placed in any environment and are exposed to constant vibrations; this increases the risk of rivets and screws loosening and causing failures. Such failures could cause a major catastrophe: wind turbines are large, and the blades are placed high up and often travel at high speeds. Using adhesives provides better stress distribution over the entire bond area instead of concentrating the stress at each mechanical fastener.

In addition, the use of adhesives makes the rotor blades lighter, providing increased efficiency. Bonding the blades also allows for more aerodynamic designs, further increasing their effectiveness. Carbon-reinforced composites are regularly used for their physical characteristics and compatibility with adhesives. Should rotor blades sustain damage from hitting flying objects, lightning strikes, edge erosion, tip fractures or delamination, the blades are repaired in situ due to the complexity and cost of transporting the blades. Adhesives play a crucial role in repairing the damage because they offer a fast processing speed and versatility that can quickly return the turbine to a serviceable condition.

FIGURE 72

A rotor blade cross-section with adhesive application points (red)



Solar power is another typical application in the renewable energy sector. Adhesives play a vital role in the development and improvement of photovoltaic cell systems, where their many benefits over traditional joining methods make their use effective. If correctly specified, the ability of an adhesive to join dissimilar materials over a wide temperature range while accommodating static and dynamic loads can be invaluable. The sealing properties of a bonded joint also contribute to the long-term protection and performance of solar power systems. Not only do adhesives allow for greater design freedom, but they also offer less obvious benefits, such as fast processing for emergency repairs or high throughput and outstanding resistance to moisture and UV. Some of the primary adhesive applications within a solar panel include frame bonding and sealing, bonding mirrors and top layers to supports, and insulating electrical components.

3.1.13

ELECTRONICS INDUSTRY

Electronic devices are everywhere. They are the computing workhorses in our offices, factories and cars; the entertainment devices in our homes; and the portable communication tools in our pockets. The latest high-tech gadgets would not exist without electronics for diagnostics, data crunching and control. Today’s electronic circuits are housed in ever-shrinking packages and engineered to withstand challenging environmental conditions – from underwater labs to space stations, and from sterile operating rooms to battered weather stations. Today’s devices can withstand all of this while meeting rigid performance requirements and regulatory mandates. Although a suitable design, installation and use of the circuitry are no doubt critical to how a device performs, the assembly and packaging of the electronics are just as important – especially if they are required to work under stressful operating conditions. Engineers are increasingly turning to adhesives over traditional soldering and joining methods to meet these design challenges.

As electronic circuits become increasingly complex, engineers find new ways to assemble and package them. Advances such as flip-chip assemblies, system-in-a-package (SiP) designs (where chips and other components are stacked on top of one another) and ultrafine-pitch electronics allow engineers to cram more computing power in smaller devices. In turn, this presents a new set of challenges that conventional manufacturing techniques cannot address. Shorter leads and interconnects increase the likelihood of thermal damage to temperature-sensitive components from the soldering process; some temperature-sensitive components must be manually assembled after soldering to avoid damage, increasing manufacturing time and cost. Ultrafine-pitch technology, packing electronics into closer quarters, can make soldering more complex and produce unreliable results, which increases the need for shielding sensitive components. All these new challenges create a need that adhesives can fulfil.

Environmental concerns pose another set of problems. Some printed-circuit assemblies must undergo post-assembly cleaning with harsh agents that can break down solder bonds. Exposure to extreme temperatures can damage bonds between components with different coefficients of thermal expansion. Excessive shock or vibration may weaken lead-free solder bonds, which are more brittle than traditional solder joints. To address these challenges, engineers turn to environmentally friendly adhesives that offer high bond strength, are electrically conductive and meet other stringent performance requirements. In this way, adhesives offer environmentally friendly alternatives to traditional materials.

3.1.14 WEARABLE ELECTRONICS

One of the fastest-growing markets is the wearable electronics market, where new applications emerge daily. Wearables encompass passive and autonomous electronic devices and span a wide range of market sectors – from infotainment and fitness to medical, industrial and military, with smart bands and smartwatches as the current application leaders. New product designs require versatile and reliable materials to achieve the ambitious development initiatives of current and aspiring manufacturers.

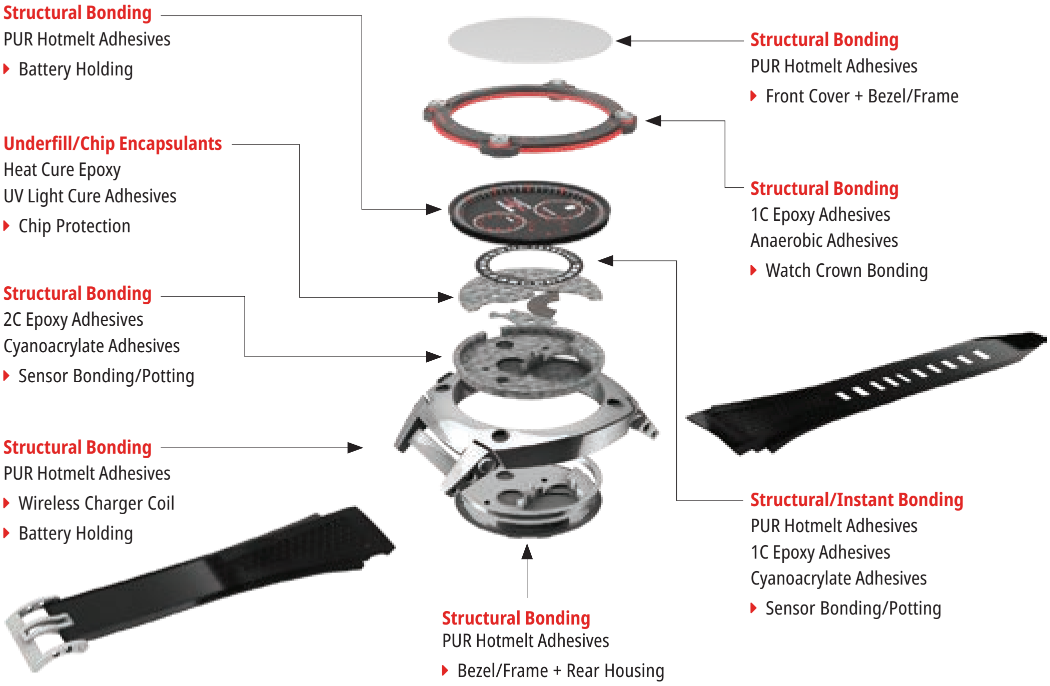


FIGURE 73

Bonding applications on a smartwatch

Structural Bonding
PUR Hotmelt Adhesives
- Battery Holding

Underfill/Chip Encapsulants
Heat Cure Epoxy
UV Light Cure Adhesives
- Chip Protection

Structural Bonding
2C Epoxy Adhesives
Cyanoacrylate Adhesives
- Sensor Bonding/Potting

Structural Bonding
PUR Hotmelt Adhesives
- Wireless Charger Coil
- Battery Holding

Structural Bonding
PUR Hotmelt Adhesives
- Front Cover + Bezel/Frame

Structural Bonding
1C Epoxy Adhesives
Anaerobic Adhesives
- Watch Crown Bonding

Structural/Instant Bonding
PUR Hotmelt Adhesives
1C Epoxy Adhesives
Cyanoacrylate Adhesives
- Sensor Bonding/Potting

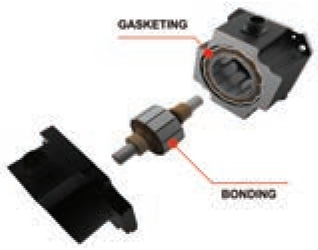
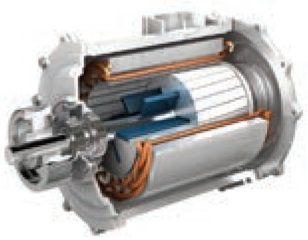
Structural Bonding
PUR Hotmelt Adhesives
- Bezel/Frame + Rear Housing

3.1.15 ELECTRIC MOTORS

Millions of electric motors are manufactured worldwide every year. While the design and performance requirements of these motors vary, their manufacturers share many of the same challenges. As technology advances, the demand for smaller motors with greater performance increases, and motors must operate at higher temperatures and at faster rotational speeds. To remain competitive, motor manufacturers must eliminate waste and become as efficient as possible. To accomplish this, design and manufacturing teams must work closely together to improve their products and processes. Electric motors are more prevalent in automobiles than ever before, forcing motor designers to find new ways to maximise performance and efficiency while being as cost-effective as possible. Electric motor and generator manufacturers have used adhesives and sealants to improve performance, facilitate manufacturing processes and reduce costs for more than 60 years. Adhesives not only make improved manufacturing processes and speeds possible but also allow designers to select new or lightweight materials to enhance performance and improve reliability.

TABLE 7

Comparison of electrical motor assembly methods

E-MOTORS	CONVENTIONAL/TRADITIONAL METHOD	ADHESIVE SOLUTION
Permanent Magnet ▸ A permanent magnet generates the necessary magnetic fields 	**Mechanical Fastening/Slots/Clips** ▸ May lead to corrosion due to the presence of gaps ▸ Involves additional process and time for magnet assembly ▸ Challenging to automate ▸ Limited impact/vibration resistance during operation at high operating temperatures ▸ Might abrade/chip the magnet's surface, resulting in repair/rework/rejections	**Magnet Bonding Solutions** ▸ Fast fixturing/curing options (<10 seconds) are available, which adhere to almost all magnetic material ▸ Automation proven for magnet bonding in E-motors ▸ More reliable and efficient; helps to avoid rework/rejection time ▸ Reduced steps/processes compared to conventional methods for magnet assembly ▸ Proven room temperature curing options available, eliminating the need for heat curing
Retaining ▸ Bearing to shaft & housing rotor to shaft 	**Press Fit / Shrink Fit / Knurling on shaft** ▸ Precise machining to achieve exact tolerances for assembly – additional time ▸ Heating and quenching process for shrink fit method for retaining assembly adds time and cost ▸ Knurling operation on the shaft – additional process	**Retaining Solutions** ▸ Allows for relaxed tolerances – no precise machining ▸ Reduced tolerance eliminates the need for a heat shrink fit and quenching process ▸ Adhesive application can be automated to control the adhesive quantity and ensure fast, reliable application ▸ Number of processes reduced ▸ Significantly reduced rework/rejection time

SECTION FOUR

THE BASICS OF BONDING

NUMEROUS FACTORS AFFECT A JOINT IN OPERATION, AND JOINTS CREATED WITH ADHESIVE BONDS ARE NO EXCEPTION. This section provides an overview of critical factors to consider when designing bonded joints. Adhesive experts, either in-house or at an adhesive manufacturer or distributor, can provide valuable insights into choosing the best adhesive for a robust, reliable and cost-effective bonded joint.

A good adhesive application depends on both the properties of the adhesive and the application itself. 'Application' in this sense is the job the adhesive is required to do, although the term is also used to describe how an adhesive is physically handled, applied and cured. The adhesive's properties, such as shear strength, fixture time, depth of cure and resistance to environmental conditions, are strongly dependent on the substrates bonded, surface preparation, how the adhesive was applied and cured, the bond geometry and the resulting distribution of stress. Process factors to consider include cycle time, required industry approvals or certifications, adhesive costs, training and equipment for dispensing and curing the adhesive.

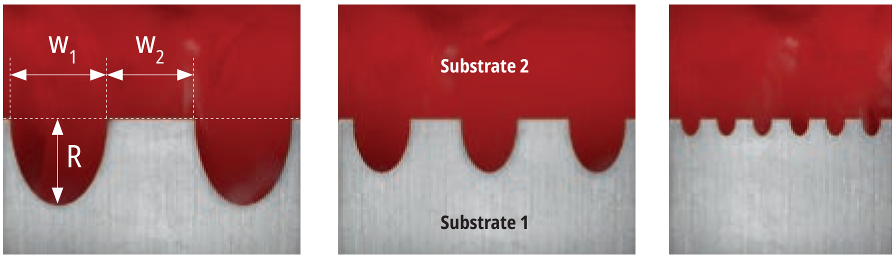
Theories related to the adhesion phenomenon include mechanical interlocking, electrostatic adhesion, diffusion and wetting. Surface preparation methods capitalise on these theories to increase bond strength.

4.1 MECHANICAL INTERLOCKING THEORY

The mechanical interlocking theory states that the adhesion between the adhesive and the substrate is the result of the penetration of the adhesive product through the irregularities or pores that the substrate may have. The surfaces are bonded to each other by the locking effect of liquid flowing into the undercuts and the additional surface area created by the irregularities and then solidifying. Increasing the surface roughness to add more cavities can increase this effect.

FIGURE 74

Increased surface area and undercuts created by an irregular surface



4.1.1 ELECTROSTATIC ADHESION THEORY

The electrostatic adhesion theory states that adhesion is a result of the electrostatic forces between the adhesive product and the material to be bonded, where electrons are transferred, forming an electrical double layer that creates attraction.

4.1.2 DIFFUSION THEORY

Diffusion theory is applicable for long-chain polymers that are capable of movement. Adhesion is the result of the diffusion of molecules between the adhesive and the surface. Depending on the adhesive's chemical properties, operational conditions and substrate, the diffusion will vary in depth.

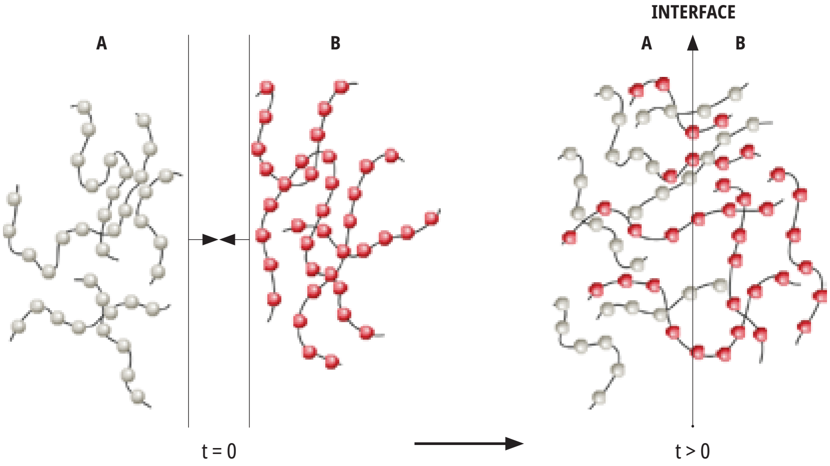
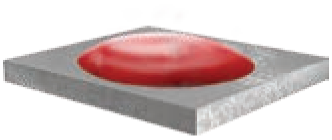


FIGURE 75

Diffusion theory of adhesion

4.1.3 WETTING AND POLARITY

Surface energy is the degree of attraction or repulsion exerted by the surface of one material to another (measured in mN/m or outdated dyn/cm). Surface tension is a liquid's resistance to surface penetration, which allows the liquid to behave like a thin elastic film. The wetting theory states that adhesion results from the surface forces of molecular contact. In the ideal bonding condition, a substrate has high surface energy, i.e. the surface has the capacity to attract, and the adhesive has a low surface tension, i.e. low resistance to deformation or breakage. This results in the adhesive properly wetting the substrate and forming a strong bond.(12) Surface preparation for bonding frequently increases the surface energy of a substrate to improve bond strength.



(>30 mN/m)

FIGURE 76

High surface energy substrate

(25-30 mN/m)

FIGURE 77

Medium surface energy substrate

(<25 mN/m)

FIGURE 78

Low surface energy substrate

TABLE 8

Substrate Polarity

SUBSTRATE	FREE ENERGY (MN/M)	SUBSTRATE	FREE ENERGY (MN/M)	SUBSTRATE	FREE ENERGY (MN/M)
Iron	2,550	Tin	700	Polyvinyl Chloride	40
Nickel	2,450	Glass	300	Polycarbonate	35
Titanium	2,050	Water	73	Polystyrene	33
Copper	1,850	Polyimide	50	Polyethylene	31
Gold	1,550	Polyamide	49	Polypropylene	29
Silver	1,250	Epoxy Resin	47	Natural Rubber	24
Aluminium	1,200	Polyamide 6.6	46	Silicone	24
Zinc	1,020	Polyethyleneterephtalate	43	Polytetrafluoroethylene	18

The surface polarity of the surface is directly related to the wetting and surface energy and affects the polymerisation reaction rate and the joint strength on a substrate. If the surface is polar, it is very reactive and will become stable after the reaction. Surface polarity is strongly related to surface free energy. Surfaces with high free energy have high polarity.

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12) S. Ebnesajjad, Handbook of adhesives and surface preparation, *Technology, Applications and Manufacturing* (2011).

TESTING SURFACE ENERGY

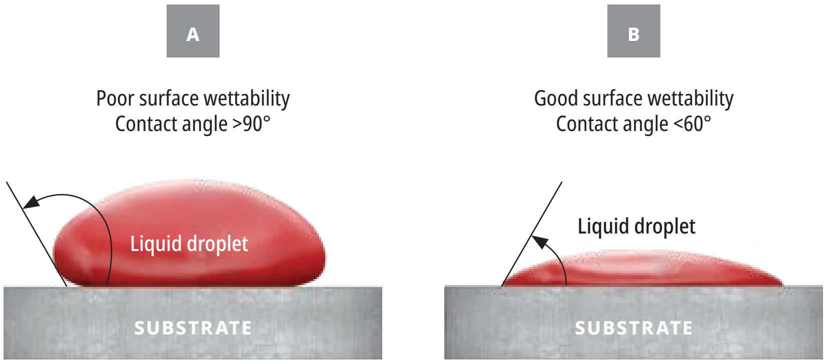
If the particular material does not have a stated surface energy, a quick and easy 'ink test' can be conducted to approximate the surface energy. The ink test is a series of solutions containing a variety of surfactants that are calibrated to specific surface tension value ranges. Each ink should be applied in succession until the appropriate level of dispersion is reached. However, this test is simply an approximation of the surface energy. To measure the exact surface energy of a substrate, the contact angle should be measured, as shown in Figure 79.

FIGURE 79

Cross-section view of a liquid droplet wetting a surface in two conditions:

A) displays poor wetting with a large contact angle

B) shows good wetting with a lesser contact angle



Put simply, surface energy is the ability of a solid surface to wet with a liquid, while surface tension is the ability of an adhesive to wet a solid surface. Based on the difference in a surface's energy and the surface tension of the adhesive, the attraction between the liquid and the solid can be measured by observing the contact angle.

The smaller the contact angle, the more attracted a liquid is to a surface and the likelier it is to wet out. An example of this in everyday life is the beading of water droplets that occurs after a fresh wax job on the exterior of a car. The wax layer effectively decreases the surface energy, leading to a decrease in attraction between the water droplets and the paint. This phenomenon can be explained by Van Der Waals forces, which are intermolecular attractive forces.(13) Not only will the surface energy of a material affect the ability of the adhesive to flow properly into the bond line and provide sufficient and homogeneous coverage of the bonding surface area, but it will often also affect the ability of the adhesive to form a strong and reliable bond. The most common unit of measuring the surface energy of a material is the dyne. Using dyne pens, this value can be found for virtually any material. Certain materials, especially common injection-moulded plastics such as PE, will have low surface energies.

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13) Joe Mausar, *'On the Surface - Surface Energy and Surface Tension,'* Adhesives and Sealants Industry, 2010.

4.2 MANUFACTURING AND ASSEMBLY PROCESS

4.2.1 OPERATOR TRAINING

A key factor to consider when addressing bonding applications is the education and training levels of the adhesive user or operator. It is important to understand how to design components for adhesive bonding and bring them effectively to production; however, the workers in production must also be trained on how to handle adhesives and complete bonding applications. While applicator training is required for many applications and processes, adhesives training for workers is often offered by the adhesive supplier as a no-charge, value-added service.

Companies that select adhesives consistently for key projects or use them to manufacture numerous products benefit from having highly skilled adhesive specialists at their disposal. The collaboration between design engineers and relevant specialists can maximise the performance, effectiveness, efficiency and quality of production processes and the final bonded assembly. Adhesive joining contrasts with many alternative joining methods (i.e. welding), where the cost to train applicators (employee time), hire qualified staff or retain skilled labourers or tradespersons is significantly higher. This is particularly important in markets with difficulty retaining skilled labour due to high wages and high demand.

TIME TO HIRE, TRAIN AND RETAIN WORKERS

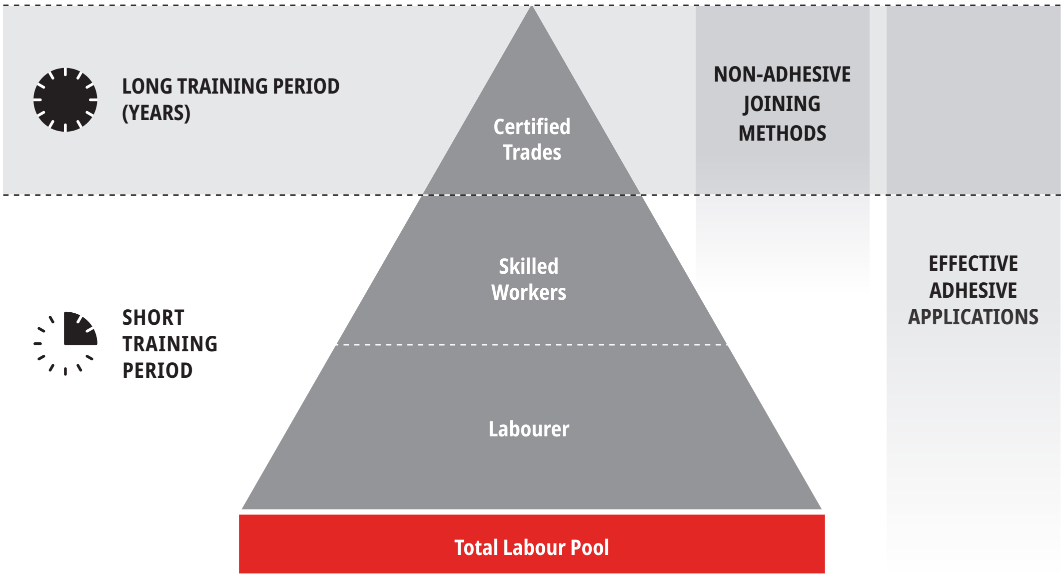


FIGURE 80

Total time investment to train workers as it relates to joining methods

Training is important due to an increasing number of industry standards requiring operators to have specific qualifications in handling adhesives from both a health and safety and a quality perspective. This addition is already part of many quality management systems and will become more critical in the future. As with any joining method, a suitable design and correct material specification can be nullified by improper use and application of the product, resulting in variable performance or even failure during operation. Therefore, training, education and quality control are vital for all aspects of joining and manufacturing. Adhesives offer a distinct advantage over other joining methods due to the ease and speed of training operators.

As mentioned previously, many manufacturing and assembly processes are currently in use. Such processes and factors must be considered when selecting an adhesive. There may be speed limitations, process limitations and health and safety factors to consider before selecting an adhesive for a given application.

4.2.2 SPEED AND THROUGHPUT

Bonding is an assembly process found in many applications and fields, whether at home as a consumer, in maintenance and repair, in the manufacturing of single parts or in mass production. Different fields and applications will have different requirements for adhesive cure speed. In ideal maintenance and overhaul operations (proactive maintenance), systematic inspections identify maintenance issues that can be rectified during planned downtime. In this instance, the cure speed of an adhesive is usually not an issue. However, on the other side of maintenance (reactive maintenance), emergency repairs can be required; here, the cure speed of the adhesive used is often one of the most critical factors.

Another factor influencing the selected cure speed of an adhesive in maintenance operations may be the environmental variation between a manufacturing environment and a maintenance environment. For example, companies will usually manufacture gearboxes for elevators under controlled, standardised climate conditions of 23°C (73°F) and 50% relative humidity. Repair or overhaul will likely occur at higher/lower temperatures and humidity, which increases/decreases the cure speed for many adhesives accordingly. These climatic conditions and their effect on cure speed should be carefully considered, particularly at temperatures below 10°C (50°F).

4.2.3 INDUSTRIAL MANUFACTURING PRODUCTION

Prototyping has become increasingly efficient since the inception of 3D printing. Materials used in prototyping might be different from the materials planned for mass production. The cure speed of an adhesive used to bond prototype parts can be longer if it is necessary to adjust the parts. A different adhesive may need to be used in the ‘Beta testing’ phase, which may change to another adhesive for mass production. Approved tests with the first adhesive will have to be repeated to choose the final adhesive.

To reduce the cure time and increase the throughput in mass production, activators or heat may be helpful for certain types of adhesives. In addition to an adhesive, mechanical fasteners, such as rivets or spot welds, can hold parts together for immediate handling. This combined use of mechanical fasteners and adhesives is often used in the automotive industry (hybrid connections). Besides immediate handling speed, these hybrid connections give the main advantage of higher strengths in, for example, a car crash, especially compared to mechanical or chemical connections alone, as the joining method.

FIGURE 81

Structural foamed pillar assembly showing greater compression strength than pure metal joined assembly during compression tests

Slow-curing adhesives can be used to connect parts that must be adjusted slightly and subsequently cured very quickly once adjusted. Epoxy or anaerobic adhesives can be quickly cured by heating the connected metal parts, for example, in an oven or induction curing.

To achieve the desired speed and throughput in manufacturing lines, the use of manual/semi-automatic/automatic dispensing equipment is essential. For more details about dispensing equipment, see Section 6.

4.2.4 PROCESS LIMITATIONS

The entire manufacturing process must be understood to determine whether an adhesive is suitable for an application. While there are numerous benefits to using adhesives, the limitations dictated by the manufacturing process cannot be overlooked. In many cases, these limitations can be overcome with process modification or by using specialty adhesives that have been designed specifically for these challenges.

COMMON PROCESS LIMITATIONS:

- Assembly exposed to high temperatures during manufacturing (i.e. paint bake cycle)
- Assembly exposed to highly caustic or acidic solutions as part of a cleaning cycle
- Extremely short cycle of assembly and testing
- Overhead or vertical adhesive application

4.2.5 HEALTH AND SAFETY

Health and safety in the manufacture and use of adhesives is extremely important as adhesives can be harmful if handled improperly. Adhesives manufacturers are required to provide accurate health and safety labelling on both the package of the adhesive and the safety data sheet (SDS). An SDS for an adhesive product contains information, including hazard identification, handling and storage recommendations, and exposure controls. The hazard identification of a specific adhesive must be considered in determining whether an adhesive is suitable for an application. Automated or manual dispensing equipment can be used to minimise potential health and safety concerns for operators wherever possible when using adhesive products.

AGENCY APPROVALS

Besides internal approvals and test methods used to verify the efficacy of the bonded assembly, external approvals may also be required, particularly in the following categories:

1. Medical
2. Potable water (for human consumption)
3. Foodstuff (direct contact or non-direct contact)
4. Fire retardant (direct exposure, flame extinguishing)

These approvals are certified by independent authorised institutes worldwide. Local validity always has to be checked; for example, potable water approvals are typically only valid if certified by local authorities.

4.3 SURFACE PREPARATION FOR ADHESIVE BONDING

Surface preparation prepares the substrate for the best possible bond. Proper surface preparation goes beyond just cleaning the substrates and includes various methods to improve an adhesive's grip on the surface of the substrate. The surface energy of plastics may be increased via plasma, corona or flame treatments for better wetting on the surface and therefore a stronger bond. An increase in surface roughness by abrasion or other methods is a proven way to increase bond strength by increasing the surface area. Chemical means of surface preparation include primers and adhesion promoters for bonding to difficult-to-bond surfaces.

4.3.1 CLEANING

Any barriers to surface contact will reduce an adhesive's bond strength. Such barriers include accidental contaminants like dirt, rust and oil or intentionally applied materials like detergents or protective films. Metal may be contaminated with cutting oil or corrosion inhibitors. Injection-moulded plastics typically have mould release on their surfaces. Table 9 shows some common sources of contamination.

FIGURE 82

Surface contamination on substrate preventing adequate adhesion

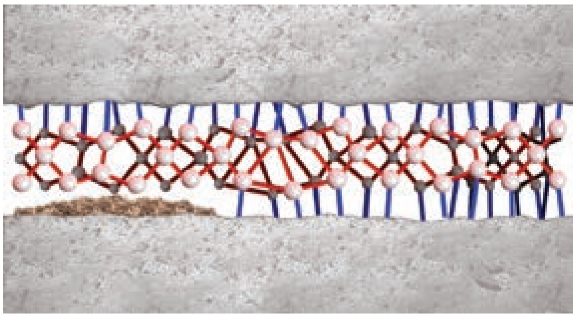


TABLE 9

Common Sources of Contamination

SOURCE OF CONTAMINATION	CONTAMINATION
Manufacturing processes	Release agents, graphite content in cast iron, drawing lubricants
Handling	Oils
Environment	Moisture, dirt and dust
Machining processes	Cutting fluids, swarf, corrosion inhibitors
Inactive layers	Oxide layers (metals) protective oil, e.g. black oxide steel bolts
Residues from galvanic processes	Metallic protective coatings like zinc, nickle, phosphate or chromate
Cleaning processes	Residues from alkaline baths or industrial cleaners, corrosion inhibitors

One cleaning step to remove all contaminants is preferable. However, depending on the nature of the contamination on a substrate, multiple methods may be required. Multiple forms of contamination are typically present, especially on used parts. In addition to removing contaminants, the cleaner used must be compatible with the substrate and the adhesive. Cleaners must also follow health, safety and environmental standards, such as those for volatile organic compounds (VOC) and biodegradability. The drying time of a cleaner and the required equipment must also be considered in the choice of cleaners. Table 10 outlines considerations when choosing a cleaning process.

TABLE 10

Cleaning Application Details and Considerations

APPLICATION DETAIL TO CONSIDER	IMPORTANCE OF CONSIDERATION
Type of Contamination	The cleaner should be selected based on the chemistry of the contamination; polar/nonpolar, inorganic/organic.
Process	**Equipment:** dip tank, spray, wipe, etc. **Time:** solvent evaporation, secondary residue removal
Parts being cleaned	Compatibility – does not chemically attack the substrate
Adhesive system	Compatibility – does not affect cure mechanism; no residue to act as a release agent
Health and Safety of Operators	Cleaners should comply with health and safety standards to protect workers and the environment.

Multistep cleaning should follow a particular order. While new parts may only need solvent or aqueous cleaning to be ready for bonding, parts with loose particulate, rust, old paint or old adhesive will require multiple cleaning steps. Before abrasion with sandpaper, wire wheel, grit blasting or other aggressive, mechanical abrasion, the surface should be cleaned with a solvent or aqueous cleaner to prevent contamination from being driven further into the surface. After mechanical cleaning or abrasion, a solvent will remove loose debris and lingering contaminants. Aqueous cleaners should not be used on freshly mechanically cleaned or abraded metal parts due to the risk of flash rust. This sequence also applies to mechanical abrasion intended to increase bond strength by roughening.

Once cleaned, parts should be bonded immediately or stored where they are protected from recontamination. Metals prone to oxidation should be bonded or treated with a rust preventative shortly after being cleaned.

The following cleaning methods may be used alone or in combination, depending on the needs of each part.

4.3.1.1 AQUEOUS CLEANERS

Aqueous, or water-based, cleaners are typically used to clean large parts or batch-clean small parts. Parts can be submerged in a heated water bath containing detergents, solvents and surfactants that attract and suspend contaminants. The cleaning cycle may include agitation or ultrasonics. Aqueous cleaning is done at about 60-80°C (140-176°F) and involves timed soaks and rinses with demineralised water. Aqueous cleaners formulated with corrosion inhibitors should be checked for compatibility with the adhesive system to be used.

The cleaning solution in a bath must be monitored and changed periodically. Energy costs include heating the baths and a heated dry cycle, which is recommended to prevent flash rust of ferrous substrates. These cleaning systems are typically not sufficient to remove heavy contamination, such as rust or paint. Used parts may therefore need a more aggressive cleaning technique in addition to aqueous cleaning.

TABLE 11

Solvent pH effect on cleaning ability for common contaminants

CONTAINMENT	ALKALINE pH 9-12	NEUTRAL pH 4-10	ACIDIC pH 1-4
Cutting Fluids	✓	✓	⊗
Greases	✓	⊖	⊗
Emulsions	✓	✓	⊗
Deep Drawing Oil	✓	⊖	⊗
Deep Drawing Soap	⊗	⊗	✓
Hard Oils	⊗	⊗	✓

✓ Recommended ⊖ Acceptable Resistance ⊗ Not Recommended

4.3.1.2 SOLVENT-BASED CLEANERS

Solvent-based cleaners are a good choice for removing oils, grease, paint, cutting fluids and moisture. An advantage of using solvent-based cleaners on metal is their ability to eliminate moisture that may cause rusting. They should be used with care on plastics as some plastics are vulnerable to chemical attack by solvents.

Solvent-based cleaning processes usually involve dip baths, closed solvent steam chambers or manual wiping processes commonly used for low part volume. While solvent-based cleaners will not dissolve metallic swarfs or inorganic contaminants, they may loosen them by eliminating any oil or grease holding them to the surface.

TABLE 12

Efficiency of solvent-based cleaners on contaminants

CONTAINMENT	HYDROCARBONS	ALCOHOLS	KETONE, ESTER
Cutting Fluid	⊖	⊖	✓
Corrosion Inhibitor	✓	⊖	✓
Waxes	✓	⊖	✓
Lubricants	✓	⊖	✓
Liquid Resins	✓	✓	✓
Liquid Adhesives	✗	⊖	⊖
Fingerprints	✗	✓	✓
Silicone Oil	✗	✗	✗
Release Agent	⊖	✓	✓

✓ Recommended ⊖ Acceptable Resistance ✗ Not Recommended

TABLE 13

Comparison of aqueous and solvent-cleaners

SOLVENT-BASED CLEANERS

BENEFITS	CONSIDERATIONS
▸ Ideal before bonding ▸ No residues left on the substrate ▸ Impurity dilution (oil, etc.) ▸ Immediate evaporation ▸ Suitable for manual cleaning processes	▸ Can attack plastics (e.g. stress cracking) ▸ No cleaning of inorganic impurities (e.g. salt) ▸ May have flammable labelling ▸ Contain VOC's (regulatory considerations)

AQUEOUS-BASED CLEANERS

BENEFITS	CONSIDERATIONS
▸ Dilution in water ▸ Biodegradable ▸ Cleans organic and inorganic impurities ▸ Compatible with most substrates ▸ No offensive smell	▸ Need to mix and monitor the specific concentration ▸ Residue may affect bonding – needs rinse stage ▸ Flash rust ▸ Need to monitor contamination of wash solution

4.3.2 MECHANICAL CLEANING

Mechanical cleaning methods are highly effective for surface preparation prior to bonding. They are also used to increase roughness and surface area for increased bond strength. Mechanical cleaning should be preceded and followed by solvent or aqueous cleaning to prevent oils and other contaminants from being driven deeper into the surface by abrasion and to clean up loose particles and lingering contaminants afterward.

FIGURE 83

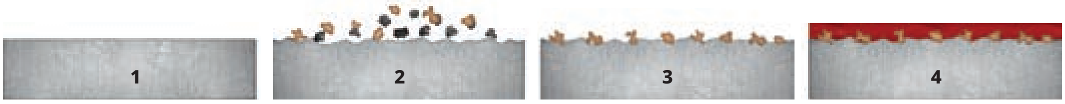
Best practice surface preparation steps when mechanically abrading

① **CLEAN SUBSTRATE** › ② **ABRADE SURFACE** › ③ **POST ABRASION CLEANING** › ④ **APPLY ADHESIVE**

There are many techniques for mechanical cleaning: by hand with sandpaper, steel wool or a wire rush or applied as a batch-cleaning with particle blasting methods.

FIGURE 84

Surface preparation with contaminated media can impact bond strength



1 Unprepared substrate

2 Grit blasting with contaminated media/air

3 Contaminated surface

4 Contaminated surface will impact bond strength

4.3.2.1 MECHANICAL CLEANING BY HAND

Mechanical cleaning by hand involves small-scale abrasion with a wire brush, sandpaper or other handheld abrasive media, all available in a range of roughnesses for everything from the removal of bulk material to polishing. Mechanical cleaning by hand requires no extra tools. The operator must control dimensional and roughness tolerances. As a rule of thumb, 120 to 180 grit sandpaper for metals and fine-to-medium abrasive fleece for plastics are recommended to prepare a surface for adhesive bonding.

FIGURE 85

Mechanical cleaning by hand

4.3.2.2 ABRASION WITH POWER TOOLS

Small handheld power tools or larger shop tools can speed the cleaning/roughening of surfaces. As in manual mechanical cleaning, a belt, rotary and orbital sanders may be used with abrasive media in a range of roughnesses; the operator must control the amount of material removed and, usually, one part is cleaned at a time.

Bristle blasting is abrasion using a rotary wire brush tool. The angle of the bristles and their acceleration as they are 'snapped' over a perpendicular bar give the bristle tips a speed and angle more like a particle-blasting treatment than a traditional rotary brush, leaving a pitted, clean surface.

FIGURE 86

Rotary wire brush tool

4.3.2.3 ABRASIVE BLASTING

Abrasive blasting cleans by shooting corundum, aluminium oxide, silicon carbide or other abrasive blasting media at a surface. Systems can work by injector, using the vacuum of a venturi nozzle to draw abrasive particles from a reservoir and shoot them at the surface or by pushing both air and abrasives from the same pressurised reservoir. Blasting systems emit dust, so they are best used in closed, covered and well-ventilated areas. These systems require trained operators and health and safety precautions for use. Figure 87 shows one of the most common surface preparation methods: grit blasting.

FIGURE 87

Grit blasting used for mechanical surface preparation

4.3.2.4 DRY ICE BLASTING

Similar in operation to injector-type abrasive blasting systems, dry ice blasting systems fire CO_2 pellets at temperatures of -78.5°C (-109.3°F) onto a part's surface. The pellets initiate a thermal and mechanical cleaning process by freezing the surface contaminants while the substrate remains at an ambient temperature. As the CO_2 pellets sublimate, they increase in volume, thereby dislodging the contaminants. This method is effective for cured adhesives, paint and other contaminants without mechanical abrasion. There is no gritty residue, no additional chemicals and less machine maintenance than traditional blasting cabinets.

4.3.3 SURFACE PREPARATION: MECHANICAL ABRASION AND ROUGHENING

Increased bond strength is a beneficial side effect of cleaning by mechanical abrasion. Substrate surfaces are frequently roughened to take advantage of this, regardless of any cleaning requirements.

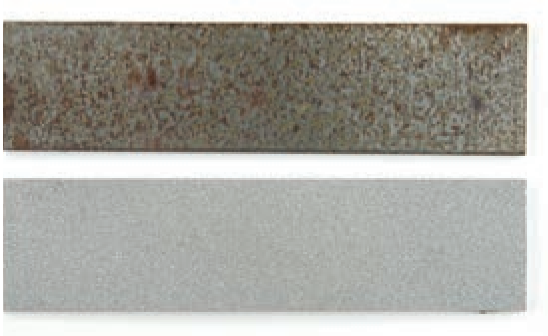


FIGURE 88

Corroded steel, prepared by grit blasting

Roughening a surface increases bond strength in two ways. The roughened surface presents a larger bond area and adhesive, which flows into microscopic cracks and porosity of the surface, cures solid and mechanically locks into the surface.

The beneficial effect of roughening substrates is measurable, as shown in Table 14.

TABLE 14

Butt joint tensile strengths with abraded aluminium substrates and an epoxy adhesive. From C.W. Jennings 1972

ADHEREND SURFACE TREATMENT	TENSILE STRENGTH N/mm^2 (psi)	STRENGTH DIFFERENCE FROM POLISHED SURFACE FINISH
Polished, 1 µ diamond dust	28.8 ± 7.0 (4,180 ± 1,020)	n/a
Abraded Through 600 paper	30.9 ± 7.7 (4,480 ± 1,120)	+ 7.2%
Abraded Through 280 paper	39.0 ± 6.8 (5,660 ± 0,990)	+ 35.4%
Abraded Through 180 paper	36.7 ± 7.5 (5,320 ± 1,090)	+ 27.3%
Sandblasted (40-50 grit)	48.5 ± 7.0 (7,030 ± 1,020)	+ 68.2%

Profilometer and scanning electron microscope (SEM) analyses show differences in surface profiles after mechanical abrasion.

FIGURE 89

Profilometer traces for aluminium surfaces

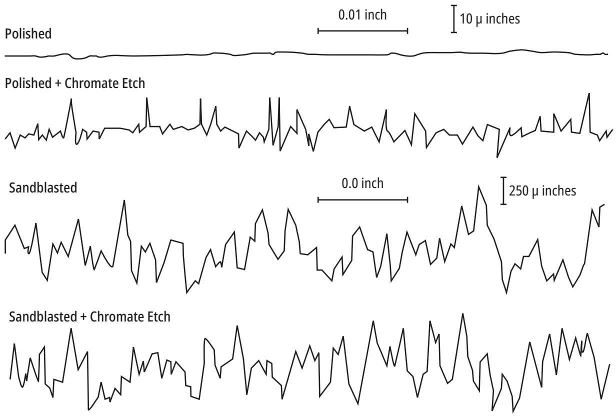
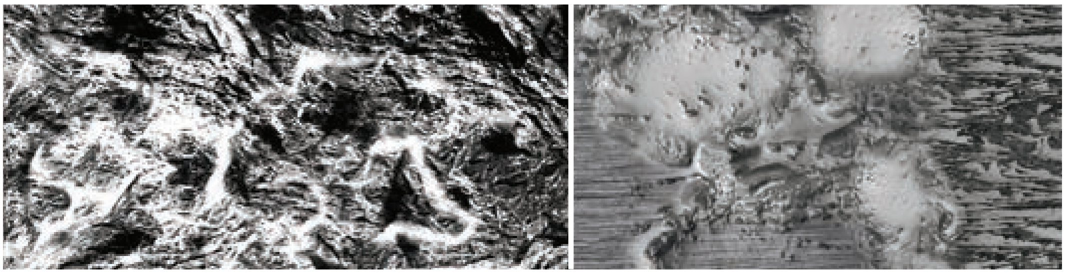


FIGURE 90

SEM images show the difference in surface roughness between a cold rolled steel plate before (left) and after surface grit blasting (right)

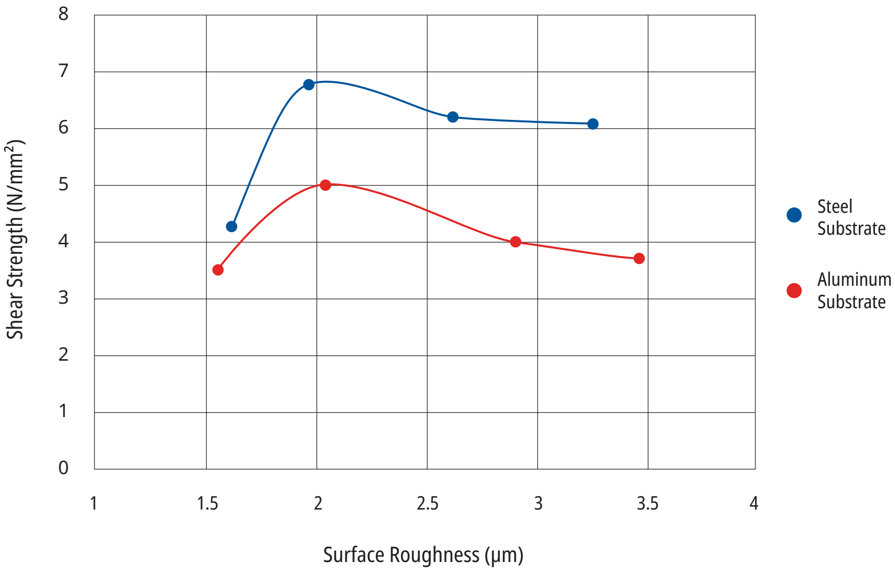


Some caveats exist for the mechanical abrasion of substrates: extreme roughness and large pores require more adhesive to fill and may take longer to cure. Adhesives that perform best in thin layers may be less effective on highly textured surfaces – check with the adhesive's manufacturer for recommended surface finishes. The cohesive strength of the adhesive layer (its internal strength) will not be increased by roughening the substrate, so assemblies suffering cohesive failure will not benefit from surface preparation.

For applications that benefit from roughening the substrate, a preferred range of surface roughness can be found experimentally. The following graph demonstrates the shear strength of an adhesive with increasing surface roughness on both steel and aluminium substrates.

FIGURE 91

Adhesive shear strength related to surface roughness of steel and aluminium (adapted from A. Ghumatkar 2016)



4.3.4 SURFACE PREPARATION: CHEMICAL PREPARATION

A substrate may be perfectly clean and still be difficult to bond. Low surface energy substrates, such as polyolefin plastics, behave like a newly waxed car, making liquids bead up instead of spreading across the surface and clinging. Wettability, the attraction of the surface for an adhesive, may be increased with a chemical primer that raises the substrate's surface energy, making the resulting adhesive bond much stronger.

Primers act as interfaces between the adhesive and the substrate. They are generally applied as a thin layer in a solvent carrier (1 g/m^2) to a low-energy substrate. In some instances, the solvent in the primer may etch the substrate and increase the surface energy/wettability to promote mechanical interlocking (Figure 93). Wetting, diffusion and mechanical interlocking theory will be covered in more detail in the following section.

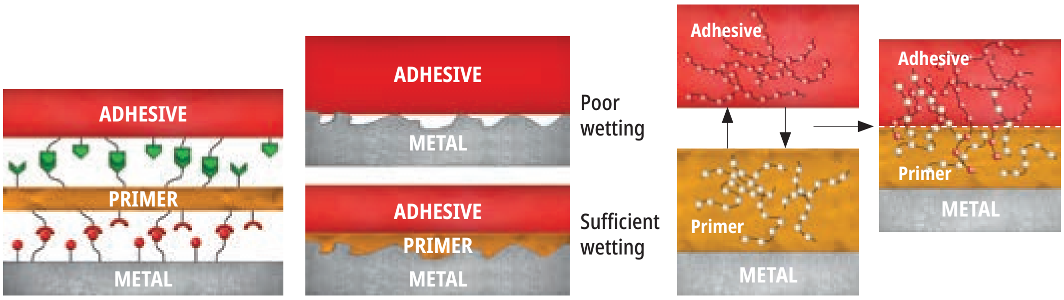
FIGURE 92

Adhesive applied to a surface with no primer (poor wetting), and adhesive applied to a surface with a primer (good wetting)

Primers may be applied to a surface by roller, brush, spray or immersion and have variable on-part lives, depending on the chemistry, substrate surface characteristics and environmental influences. Each primer is specifically designed for specific substrates and adhesives, and a primer designed for one chemistry or substrate may not be suitable for another substrate or chemistry.

FIGURE 93

Functions of primers in facilitating adhesion



4.3.5 SURFACE PREPARATION: CHEMICAL ACTIVATORS

There are several methods to artificially (but temporarily) increase the surface energy to prepare low-energy surfaces for bonding. First, primers may be used to increase adhesion or reactivity of adhesive products on these surfaces. Second, corona or plasma treatments may be used to increase the surface energy (Figure 94). The amount of increase in energy is often related to the intensity of the treatment, the proximity of the treatment device to the surface and the amount of time the surface is treated.

Activators are often confused with primers, but where primers (and all other surface preparation) affect the substrate surface, the role of an activator is to work directly with the adhesive. Activators carry a chemical component necessary for the adhesive to cure or increase its cure speed. As a surface preparation, they may be applied to one surface and the adhesive applied to the other. In some cases, as for anaerobic adhesives that require active metal to cure, the activators add active metal ions to inactive surfaces, such as stainless steel. Some two-part mixed adhesives have an 'activator' component, but these are mixed before application and not applied alone to surfaces. Similar to primers, activators designed for one type of adhesive may not be suitable for another type.

4.3.6 ELECTROCHEMICAL SURFACE TREATMENTS

Electrochemical treatments increase the surface energy of plastics that are difficult to bond. The most common forms of electrochemical treatment include plasma, corona and flame treatment.

4.3.6.1 PLASMA TREATMENT

FIGURE 94

Surface activation by plasma treatment

Plasma treatment increases the bondability of a substrate by bombarding the substrate surface with ions of a gas, such as argon, helium, nitrogen and oxygen, at low pressure. Several mechanisms have been proposed to explain the enhanced bondability created by plasma treating. For example, plasma treatment is hypothesised to crosslink the substrate's surface, strengthening the joint boundary and preventing a thin layer of the substrate from peeling off. In addition, the surface oxidation caused by plasma treatment introduces reactive functionalities, which then increase the surface's reactivity and wettability. Another theory attributes the effectiveness of plasma treatment to an increased interfacial diffusion created by chain scissions in the substrate's surface. The interfacial diffusion is increased by lowering the surface viscosity and increasing the molecular mobility of the plastic's surface.

These methods work by blasting a surface with free electrons to increase the dyne level, but this method usually only temporarily increases the surface energy, so bonding must occur immediately after the treatment steps.

4.3.6.2 CORONA DISCHARGE

In a corona discharge process, a hard-to-bond plastic is exposed to an electrical discharge, usually in the presence of air and at atmospheric pressure, which creates a plasma 'field'. This roughens the surface, which provides sites for mechanical interlocking and introduces reactive sites on the plastic's surface, consequently increasing the wettability and reactivity of the surface. The reactive functionalities, which are theorised to be introduced to the surface, may include carbonyl, hydroxyl, hydroperoxide, aldehyde, ether, ester and carboxylic acid groups, as well as unsaturated bonds.

4.3.6.3 FLAME TREATMENT

Flame treatment increases the bondability of plastic by oxidising the surface through brief exposure to flame. The oxidation proceeds as a free radical mechanism, accompanied by chain scissions and some crosslinking. The functionalities introduced by oxidation are hydroxyl, carbonyl, carboxyl and amide groups, with a typical oxidation depth of approximately four to nine nanometers. Wettability is improved by increased surface energy. The chain scissions on the surface contribute to higher interfacial diffusivity.

4.3.6.4 THERMAL SURFACE TREATMENT

Thermal treatment increases the bondability of plastics by exposing the plastic to a blast of hot air (approximately 500°C/932°F), which oxidises the surface. This method mainly introduces carbonyl, carboxyl and amide groups to the surface, but some hydroperoxide groups are also formed. Very similar to flame treatments, this process also utilises a free radical mechanism accompanied by chain scission and some crosslinking. The improved bondability results from increased wettability due to the introduction of polar groups and interfacial diffusivity caused by chain scissions.

4.4 STRESSES ON JOINTS

Adhesive performance is measured by its resistance to the forces acting on the bonded assembly. Laboratory results on standardised specimens, available in the adhesive manufacturer's published technical data sheets (TDS), are an excellent tool for identifying candidate adhesives for an application. Adhesive candidates chosen based on these generic results should then be tested rigorously with simulated or actual end-use parts, assembly processes and operating conditions.

The physical forces acting on a joint may be classified as shear, tensile and compression loads, etc. They rarely occur purely as one type; in fact, some combinations are so common that they have their own names, such as peel or cleavage loading. Stress may occur at high speeds in the form of impact or as cyclic fatigue loads, and it may be static or dynamic. Thermal effects may impose stresses with differential expansion and contraction of a substrate or assembly. The more accurately these conditions can be simulated in testing, the better the prediction of the final assembly's performance.

'Force' refers to the entire load acting on a joint or assembly. 'Stress' is force divided by the area supporting it; therefore, a small area results in higher stress. For mechanical fasteners and linear joints, such as welds, the force is concentrated in a relatively small area. Adhesive bonds can spread the force over a larger area, resulting in lower mean stress.

Mechanical and thermal joints manage stress differently from adhesives, as the following lists show:

MECHANICAL FASTENERS AND THERMAL JOINING

- Create stress concentration points that may lead to substrate distortion or cracking
- Rely on bosses or holes that can weaken the structure and add machining costs
- Require reinforced connection points for concentrated stresses, increasing cost and weight
- Cause the applied load to be carried by a small area of the fastener
- Require tight tolerances
- Alter the substrate's material properties with high temperature exposure (welding)

ADHESIVE BONDS

- Distribute stresses and loads evenly across the bonded joint
- Eliminate the need for bosses and holes, limiting manufacturing stresses and fractures
- Compensate for more relaxed tolerances with gap-filling ability
- Seal, as well as join
- Can join a wide variety of geometries and materials

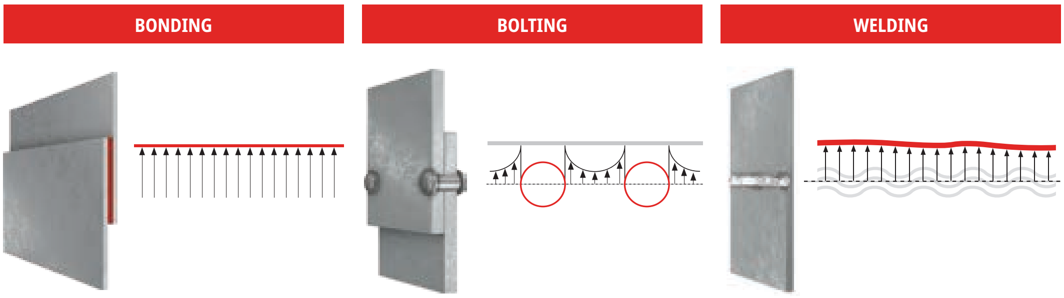


FIGURE 95

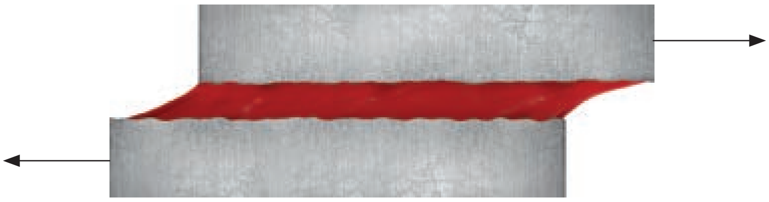
Stress distribution of common joining methods

4.4.1 SHEAR STRESS

Shear stress results from the force applied parallel to the joined surfaces. Adhesive shear strength is an adhesive bond's resistance to this stress and is reported in the load per area of the bonded overlap.

FIGURE 96

Forces showing shear stress



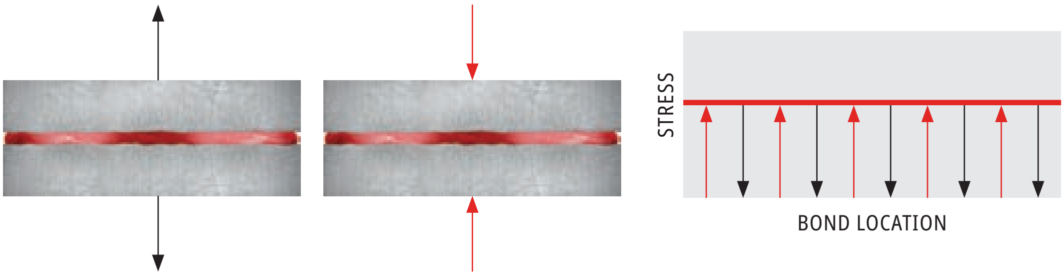
The shear strength reported on an adhesive's TDS is the product of testing on standardised specimens. These data points are a good screening tool for selecting adhesives to test on actual or prototype assemblies, which will have a different geometry and stress distribution than the standardised tests and are necessary to accurately predict the joint's reliability. The most common standardised shear strength test is the single lap shear test (ASTM D1002, ISO 4587). This test excels as a quality control (QC) check in detecting variation in the same adhesive and substrate combination, but changing stress distributions for different adhesive/substrate combinations make it problematic for comparing different materials, particularly those with different moduli (stiffness). Even more problematic (and this is true for any standardised strength test), it has limited ability to predict performance on geometries found in real-life assemblies. Testing on real-world assemblies under real-world conditions is essential to predict the performance of the bonded joint accurately.

4.4.2 TENSILE STRESS

Tensile stress occurs when force is applied in a direction to elongate a material. Testing for adhesive tensile strength may be performed on cured homogenous specimens of the adhesive itself. These tests produce tensile property data that may include tensile strength in units of load per cross-sectional area, elongation in percent of the original length, tensile modulus (stiffness) and yield point. Tensile modulus is measured as the slope of the stress-strain plot in the Hookean or linear initial portion of the test; the units are the load per sectional area. Tests for bonded assemblies, such as the butt-joint test, apply force perpendicular to the plane of the bonded surfaces to pull them apart. These results are reported as loads per cross-sectional area and failure mode (see Section 7 for further discussion on failures).

FIGURE 97

Tensile and compressive stress distribution on a bonded assembly



4.4.3 COMPRESSIVE STRESS

As implied by its name, compressive stress exerts a force that compresses a material. The force pushes in towards the centre of the material. A typical test done on cured cylinders of adhesive, ASTM D695, reports compressive strength, compressive yield strength and modulus of elasticity.

4.4.4 PEEL STRESS

Peel stress is primarily a combination of shear and tensile stresses. Peel geometry varies with substrates, bond strength and the angle of separation, but what peel situations have in common is that at least one substrate is flexible enough to be bent back and pulled away from the other by the applied force. Separation begins at one end and progresses along the length of the bond like a zipper, with the stress concentrated at the leading edge. More and more of the substrate is progressively debonded as the free end is pulled away from the opposite substrate. The stress-strain plot of a peel test typically shows an initial peak when the peel begins, followed by a plateau of relatively even stress as the specimen is peeled apart, with stress dropping to zero at full separation. Peel strength is typically reported as the average value of this plateau in force per unit width. Failure mode may also be reported.

FIGURE 98

Peel force stress distribution on a bonded assembly

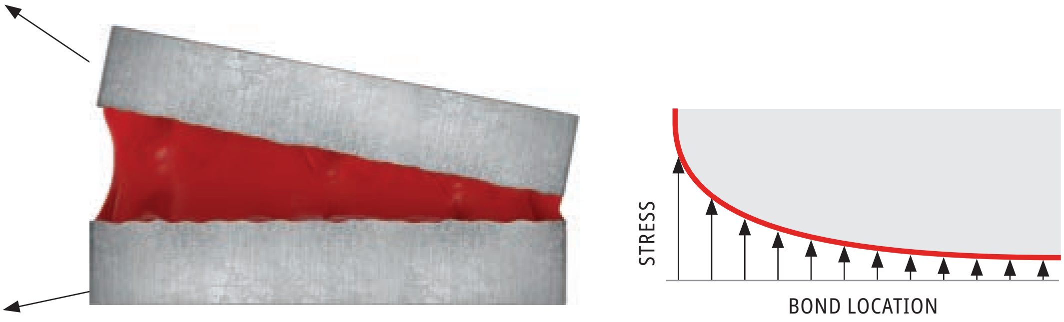
Peel tests measure the average force required to fracture the adhesive bond between flexible materials when pulled at a specified angle. A common test to evaluate peel stress performance of an adhesive is T-Peel ISO 11339.

4.4.5 CLEAVAGE STRESS

Cleavage stress occurs when rigid substrates are opened at one end. Standardised tests to simulate cleavage stresses are done by gripping the ends and pulling apart or by driving a wedge between the substrates through the adhesive layer. This test is particularly important for measuring properties related to crack propagation in adhesives.

FIGURE 99

Cleavage stress distribution on a bonded assembly



4.4.6 IMPACT STRESS

Impact is dynamic stress at high speed. Impact stress may be applied as compression, tension, shear, cleavage, peel or any combination of these. The toughness of the substrate and the adhesive will be key in resisting impact stress. A strong material under static loading may fail under impact if it is brittle.

The impact resistance of a material or an assembly depends on its ability to move or deform to accommodate the impact internally. In a bonded assembly, the toughness of the substrate and adhesive and how the geometry distributes the impact throughout will determine the assembly's toughness and resistance to impact.

There are many tests for impact resistance, including drop tests (compression), side-impact (shear) and wedge impact (cleavage). Testing may be done on homogenous cured samples or assemblies, either standard test specimens or end-use assemblies. Results are typically reported in units of work (force x displacement), or joules, required to break the sample bond. The graph in Figure 100 illustrates other useful information such as joint behaviour and force to initiate failure.

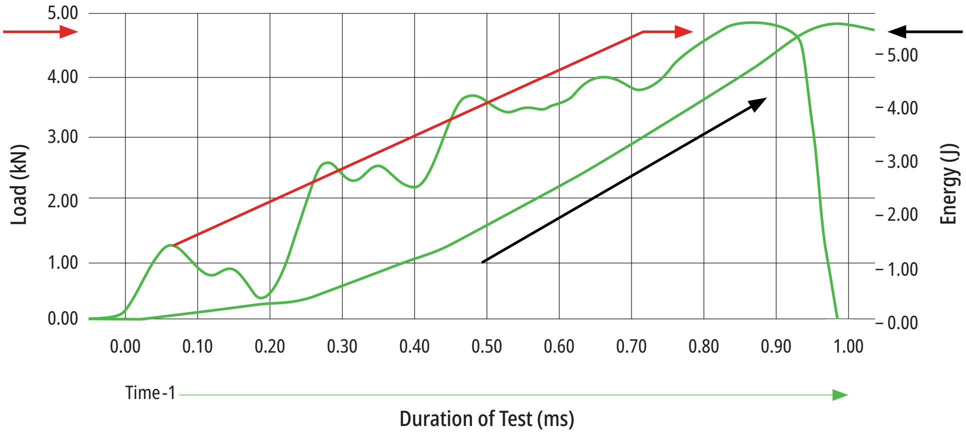


FIGURE 100

Stress-strain curves showing impact testing

Impact test software produces a dynamic load graph that starts when the sample is first impacted and records the loading of the sample until rupture. Whereas static testing may be measured in seconds or minutes, an impact test is measured in milliseconds.

- The upper jagged green/red lines indicate the load applied to the sample over time. When the load drops below zero, the sample has broken.
- The lower green line/blue lines follow the total absorbed energy over time and level off when the sample breaks, showing that energy is no longer being absorbed.

4.4.7 FATIGUE STRESS

Fatigue stress is repetitive cyclic loading. The vibration from traffic on a bridge, persistent force on a wind turbine, keystrokes on a keyboard and automotive shock absorbers are all examples of fatigue stress. Like impact, fatigue is a dynamic form of stress.

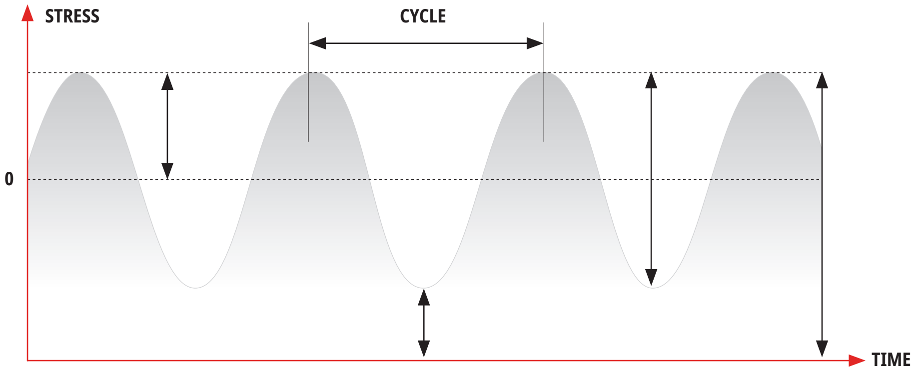


FIGURE 101

Stress-strain curve showing cyclic forces

A material or assembly that will withstand a large static load may fail at a much lower load if it is cyclic and repetitive. Fatigue testing seeks to predict the working life of an assembly by testing specimens under cyclic loading at multiple stress levels. Life cycle predictions based on these results may be used to schedule the replacement of these parts before the anticipated failure.

Fatigue parameters include amplitude, frequency and wave shape. Polymers (adhesives included) are normally tested below a frequency of 60 Hz to avoid heating the material, which would introduce an unwanted condition into the test. One hundred percent strength is determined by testing the specimen to failure in a static test; fatigue cycling is then performed at ever-decreasing levels until a level is reached that will endure 'indefinitely', or 10^7 cycles, as a practical rule-of-thumb. An S-N graph is plotted with stress on the y-axis and the number of cycles on the x-axis. A best-fit line that appears asymptotic indicates that the assembly may survive indefinitely at this stress level: ISO 9664 defines this as the fatigue limit. If the plot continues to slope downward at 10^7 cycles, this is reported as the endurance limit at 10^7 cycles. *Note: ASTM uses slightly different terminology; the identification of test results must reference the source test for clarity.*

S-N Curve for steel:

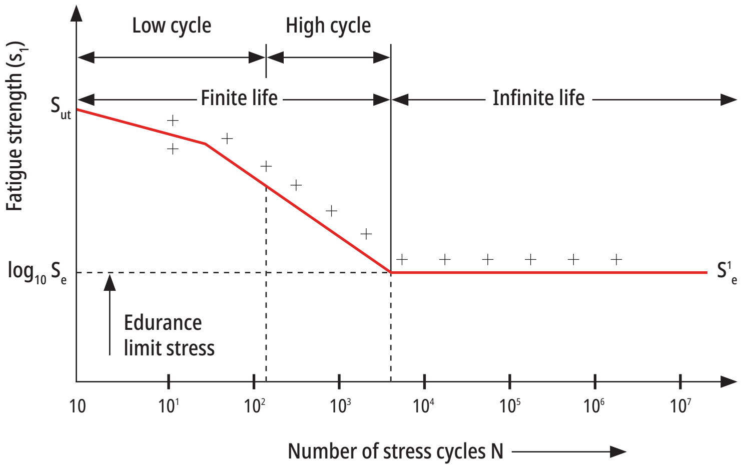


FIGURE 102

Steel produces an asymptotic S-N plot

4.4.8 THERMAL EXPANSION

All materials expand and contract with temperature changes. However, when two joined members have different thermal expansion rates, a temperature change will cause one member to expand more than the other. In an inline six-cylinder automobile engine, differing expansions can cause as much as a 1.5 mm (~0.060 ft) total change to the cylinder heads under extreme temperature cycling. When the change in expansion and contraction is restrained, it induces thermal stress. For a properly bonded or joined assembly, adhesive strength or friction resists the stress, but when the thermal stress exceeds adhesive strength or friction, the joined assembly will begin to fail. For every temperature cycle, excess stress will lead to further separation until critical failure occurs. When assessing the assembly to be bonded, the coefficient of thermal expansion and contraction of each substrate must be known. If the coefficients of thermal expansion and contraction are significantly different, thermal cycling and hot strength testing are recommended to verify the adhesive’s performance under applicable thermal extremes.

4.5 ENVIRONMENTAL FACTORS

For an adhesive or sealant bond to meet the application requirements, it must withstand the mechanical forces acting on it and the working conditions to which it is exposed. These conditions may include temperature extremes, humidity, chemical exposure, UV light and outdoor weather.

4.5.1 EFFECT OF THE ENVIRONMENT

As the environment to which an adhesive bond is exposed can degrade the adhesive's polymeric structure, influencing the cohesive bonds or undermining the bond with the surface, it is necessary to evaluate the environmental conditions and the mechanical forces to which the joint will be exposed.

Adhesives may see varied outdoor climates, such as semi-arid, tropical and coastal climates. Specific standards are designed for gauging the effect of these conditions, real-time or simulated, on bonded assemblies. Aside from external environments, the application can impose severe conditions. Extremes in major appliances like ovens, freezers and dishwashers, and in automotive engines, aerospace and medical device sterilisation should all be anticipated and tested before an adhesive bond is green-lighted for production. It is important to test both environmental and physical stresses concurrently, as the additive effect may be more severe than each individually. The good news is that adhesives are so versatile that there are choices for almost every situation. Adhesive manufacturers and distributors can provide expert advice on applying adhesives in extreme environments.

4.5.2 OPERATING TEMPERATURE

All adhesives have a certain temperature at which they undergo degradation. This may occur with brief excursions at high temperature or through long-term thermal ageing. Each chemical type of adhesive and its different formulations will have their own response to thermal conditioning. Cohesion may be weakened, or it may become more brittle and less able to absorb shock, impact or temperature-related dimensional changes. The key properties for good high temperature performance are a high glass transition temperature and resistance to oxidation.

Thermoplastic adhesives can provide excellent cohesive bonds at room temperature. As the working temperature approaches the glass transition temperature of the adhesive, the plastic flow results in bond deformation and cohesive degradation.

Thermoset adhesives consist of crosslinked polymeric chains and have no melting point. When thermoset adhesives are exposed to high temperatures, the critical factor is the rate of force reduction due to thermal oxidation and pyrolysis. Thermal ageing can also affect the adhesion interface, causing chemical and physical changes. Thermal oxidation initiates a progressive split of the chain of molecules, resulting in a loss of weight, strength, elongation and toughness within the adhesive or sealant. Pyrolysis is the simple thermal destruction of the molecular chain of the base polymer in the adhesive or sealant formulation. Pyrolysis causes cleavage of the chain and a decrease in the molecular weight of the polymer, which results in reduced cohesive strength and fragility.

To be considered suitable for applications at high temperatures, an adhesive must provide all the usual functions necessary for good adhesion (wettability, low shrinkage during curing, a similar coefficient of thermal expansion to the substrates, etc.) and must have a high melting point and glass transition temperature (Tg), resistance to oxidation degradation and thermally induced chain break resistance.

Many adhesive and sealant applications require both high- and low-temperature performance. The critical factors to consider for wide temperature range applications are the difference between the coefficients of thermal expansion for adhesive and substrate (the closer the better), the elasticity modulus of the adhesive at application temperatures and the thermal conductivity of the adhesive.

The difference in the thermal expansion of the adhesive and substrates is important at low temperatures, especially because the modulus of elasticity of the adhesive generally increases (it becomes stiffer and more brittle) with decreasing temperature to a point where the adhesive can no longer effectively release concentrated stresses.

4.5.3 HUMIDITY AND WATER

The high polarity of water can lead to the weakening of bonded assemblies. All polymers absorb water to a certain extent. Although its effect on the interface is fundamental, water can also change the adhesive properties by changing the glass transition temperature and inducing cracks or chemical reactions.

The humidity of the environment can affect the adhesion force in two significant ways. Some adhesives will lose hardness, temperature resistance and, in the worst case, liquefy during exposure to hot and humid air. Water can also permeate the adhesive and displace the adhesive at the joint interface. This mechanism is the most common cause of reduced adhesive strength in humid environments.

The adhesion force deteriorates more quickly in an aqueous vapour environment than in liquid water due to faster water vapour penetration. Primers and surface treatments tend to prevent degradation of the adhesion force in humid environments.

In the case of substrates that are vulnerable to water and humidity, degradation of the substrate at the interface, regardless of any direct effect on the adhesive, will compromise the bond.

4.5.4 CHEMICAL EXPOSURE

There is no single adhesive that is ideal for all chemical environments. Some families of adhesives, such as epoxies, are know to have broad resistance to many types of chemicals. PUs, silicones, acrylics and UV curing adhesives can provide acceptable chemical resistance against a certain range of chemicals, although they cannot withstand as many chemical environments as epoxies. The chemistry of an adhesive can vary substantially, even within a family. Two adhesives from the same family may have different additives and curing reactions that affect their chemical resistance.

There are two properties of adhesive joints that protect them from exposure to chemical or solvent environments. The high degree of crosslinking of the chain, found in such thermoset adhesives as epoxies, phenolics, PUs and modified acrylics, tends to resist various chemicals when exposed to temperatures below the glass transition temperature (Tg). Therefore, adhesives with higher Tg can often resist higher temperatures and tolerate more chemicals. Another important property of good chemical resistance is the area of bond exposure to the chemical. The thinner the bond line, the less direct contact with the chemical itself, which protects the adhesive from exposure. This is especially true if the substrates are neither porous nor permeable to the chemical environments in question.

In the families of adhesives and their possible applications, it is necessary to consider chemical and thermal resistance together. The temperature of the chemical medium in which an adhesive joint is immersed is a significant factor in the ageing properties of adhesives. As the temperature increases, the fluid absorption by the adhesive increases and the rate of degradation increases. In general, chlorinated solvents, ketones and high boiling solvents, such as dimethylformamide and dimethyl sulfoxide, are considered harsh environments.

4.5.5 UV RESISTANCE

The adhesive used in external applications or applications in transparent or translucent substrates may be exposed to UV light. Exposure to sunlight and some artificial lights can have adverse effects on the performance life of adhesives or sealants. UV radiation can break the chemical bonds in a polymer. This process is called photodegradation and can ultimately cause cracking, scaling, colour changes and loss of the physical properties of an adhesive. Where resistance to UV light is a concern, absorbers and inhibitors of UV radiation may need to be added as surface coatings or additives.

The important aspect is that once photodegradation has started, it triggers a circular chain reaction that accelerates degradation, unless stabilisers are used to interrupt the oxidation cycle.

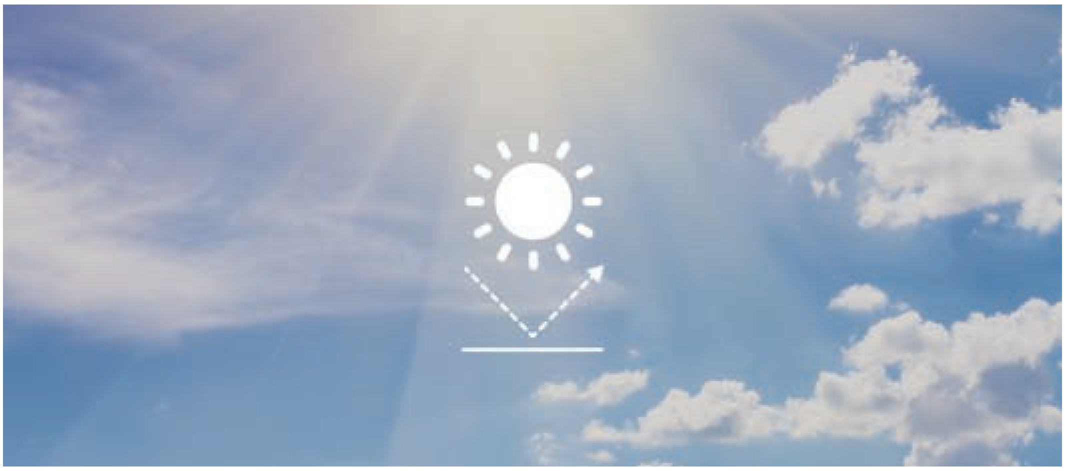


FIGURE 103

UV radiation may cause degradation of properties

TABLE 15

Summary of adhesive environmental conditions resistance

	TEMPERATURE RESISTANCE	MOISTURE	CHEMICAL	UV
2C Epoxy	High -55°C to 121°C (-67°F to 250°F)	Excellent	Excellent	Good
1C Polyurethane	Medium -40°C to 80°C (-40°F to 176°F)	Moderate	Good	Poor
2C Polyurethane	Medium -40°C to 130°C (-40°F to 266°F)	Moderate	Excellent	Moderate
Reactive Hotmelt Polyurethane	Medium 130°C (266°F)	Moderate	Good	Moderate
Modified Silicone Polymer	Medium 80°C (176°F)	Moderate	Good	Excellent
1C and 2C Silicone	Very High 200°C (392°F)	Good	Excellent	Excellent
Anaerobic	High -55°C to 121°C (-67°C to 250°F)	Good	Excellent	Excellent
Acrylic	High -55°C to 120°C (-67°F to 248°F)	Good	Good	Good
Cyanoacrylate	High -55°C to 120°C (-67°F to 248°F)	Poor	Moderate	Good

SECTION FIVE

APPLICATION AND BOND PROCESS

THIS SECTION OUTLINES THE MOST COMMON TYPES OF ADHESIVE JOINTS, HOW THEY ARE USED AND SOME OF THE SHORTCOMINGS AND COMMON PROBLEMS OBSERVED WITH EACH JOINT TYPE. When creating a design, adhesives may be the sole fastening device or used in conjunction with some alternative fastening devices, such as screws or rivets. Whether an adhesive is used as the primary fastening method, secondary fastening or simply as a sealant depends on the properties of the adhesive and the process time.

5.1 ADHESIVE JOINT DESIGN

5.1.1 ASSEMBLIES AND JOINT STRESS DISTRIBUTION

Alternative joining techniques, such as welding or riveting, have specific benefits in certain situations, such as extreme temperatures and harsh chemical environments, where adhesives may not be suitable. However, in nearly all other circumstances, adhesives can provide an exceptionally robust and reliable solution if the assembly is designed correctly. Adhesive assemblies excel with the uniform distribution of stress, and a well-designed assembly will often be stronger than many alternative joining methods such as riveting or bolting.

As shown in Figure 104, the stress distribution of adhesive bond lines is significantly more uniform than bolting or even welding. The even stress distribution exhibited by a correctly designed bond line has several advantages. It will primarily help prevent substrate fatigue and create a stronger, more impact-resistant assembly.

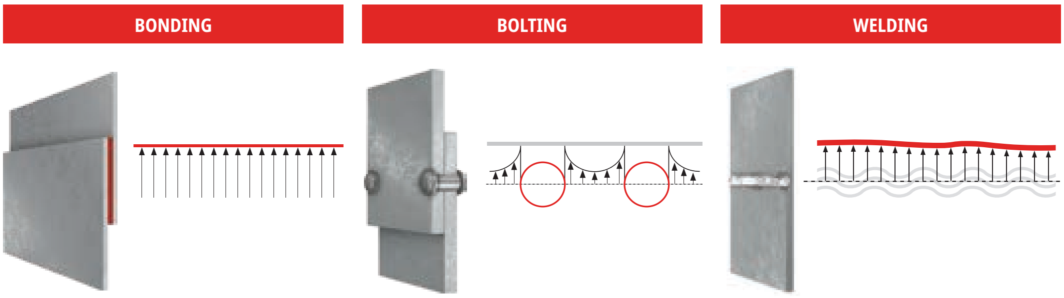


FIGURE 104

Different types of joints and their stress distributions. Referring to the previous classification, periodic is bolting, welding is linear and adhesives is area

Adhesives can be used successfully in a wide range of processes and can be integrated into nearly any manufacturing environment. As shown in Table 16, adhesives can offer various benefits that many alternative joining methods do not, such as invisible application or increased aesthetics, better stress distribution, uniform strength across the assembly, no surface/substrate damage, no corrosion and decreased parts inventory. While commonly used to bond similar substrates, adhesives are often the only choice for bonding dissimilar substrates.

TABLE 16

Comparison of traditional joining methods vs using adhesives technologies

CONTAINMENT	ADHESIVES	BLIND RIVET	WELDING	SCREW	NUT, BOLT & WASHER	TUBULAR AND SEMI-TUBULAR RIVET	SOLID RIVET
Invisible in application	✓						
Stress distribution	✓						
High tensile & shear strength	✓		✓		✓	✓	✓
Different materials	✓	✓	✓	✓	✓	✓	✓
Can join different materials	✓	✓		✓	✓	✓	✓
High and low temperature resisitance	✓	✓	✓	✓	✓	✓	✓
No hole required	✓		✓			✓	
Vibration resistant	✓		✓				
Uniform strength	✓		✓				
All work done from one side	✓	✓	✓	✓			
Eliminates heat distortion	✓	✓		✓	✓	✓	✓
Clean appearance/aesthetics	✓						
Fastens in one operation	✓	✓		✓		✓	
Joins without bulky equipment	✓	✓		✓	✓		
Pressure-tight (without seal)	✓		✓				
Tools readily available	✓	✓		✓	✓		✓
Can be installed without power	✓	✓		✓	✓		✓
Small capital investment	✓	✓		✓	✓		✓
Minimum equipment needed	✓	✓		✓	✓		✓
Tamper resistant	✓	✓	✓			✓	✓
Holds plastic	✓	✓		✓	✓	✓	
Easy alignment of work surfaces	✓	✓		✓	✓		✓
Prevents surface damage	✓						
Minimum back-up space	✓	✓	✓			✓	✓
Flush finish	✓			✓			
Wide grip range	✓	✓	✓	✓	✓		
Low parts inventory	✓		✓				
Eliminates equipment adjustment	✓			✓	✓	✓	✓
Requires minimal set-up time	✓	✓	✓	✓	✓		

5.1.2 TYPES OF JOINTS

The ideal bonded joint is one that, under all practical loading conditions, the adhesive is stressed in the direction in which it most resists failure. A suitable joint design can be used to reduce the effects of stress on the bond line. However, some joint designs may be physically or aesthetically impractical for a particular assembly, expensive to implement or hard to align. The design engineer will often have to weigh these factors along with optimal adhesive performance. The most common and cost-effective joint designs are discussed in the following sections.

5.1.3 PLANAR SUBSTRATES

5.1.3.1 HEAD-TO-HEAD OR BUTT JOINTS

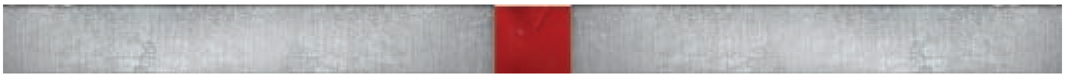
Head-to-head joints, also known as butt joints, are simple joints obtained by joining only the ends of the pieces to be bonded; the bonded surfaces are perpendicular to the plane of the substrate. These joints are generally avoided because of their inability to withstand bending stresses or any impact stresses perpendicular to the plane of the substrate; these will almost certainly lead to adhesive failure. While butt joints are the weakest joints that can be created, they are commonly found because they are the easiest to make.

If the thickness of the substrate is too great to make an overlap joint or if a butt joint is the only solution due to engineering or repair limitations, 'modified' joints can be employed to increase resistance against buckling (see Single Strap Joint, Figure 109).

Since the butt joint is weak, it is usually only used in simple situations and should be avoided in engineered applications or assemblies.

FIGURE 105

Butt joint or head-to-head joint



5.1.3.2 SCARF JOINT

A scarf joint is a type of overlap joint where the angle between the substrates is greater than 0 degrees but less than 90 degrees. For example, two substrates cut at opposing 45-degree angles and bonded together would form a scarf joint. The substrates must be of equal thickness and width to form an effective scarf joint in this application.

The scarf joint is commonly used to build large composite structures piece by piece or to repair damaged composite structures. The scarf joint interface has no continuous reinforcement from one side to the other; however, the closer the scarf joint angle is to zero, the greater the bond overlap surface area; this will maximise the strength in this joint.

The scarf joint is a suitable alternative to other joints, such as the butt joint and splice joint, and is often preferred because it produces a barely visible bond line.

FIGURE 106

Scarf Joint

5.1.3.3 DOUBLE BUTT JOINT OR HALF LAP

The double butt joint or half lap joint is obtained by machining the ends of substrates to increase the contact surface. By increasing the contact surface, forces exerting stresses on the assembly will be distributed more evenly, thus creating a stronger joint. Generally speaking, half the depth of the material will be removed from each substrate (assuming equal dimensions) to maintain maximum substrate integrity. This joint is reasonably strong; however, it is not recommended when materials are subject to fatigue or high-impact loads. Preparing the joint is simple, but it must be fitted correctly along the entire length of the joint to ensure adequate strength.

FIGURE 107

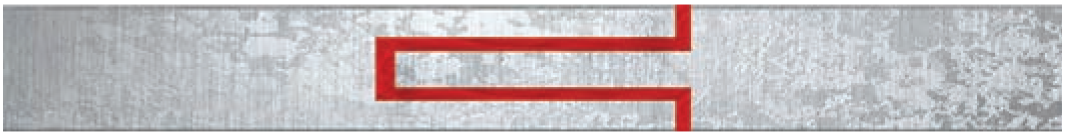
Double butt joint

5.1.3.4 TONGUE AND GROOVE JOINT

A tongue and groove joint is made with an edge that consists of a groove running the entire length of the joint and a tongue that fits into the groove. This feature of the tongue and groove creates a mechanically strong and aesthetically pleasing joint. The greater the contact surface, the greater the distribution of stresses along the contact surface. This joint is well suited to a number of stresses, as the joint geometry counteracts many of the weaknesses exhibited under peel stress or stresses perpendicular to the bond line.

FIGURE 108

Tongue and groove joint



5.1.3.5 STRAP JOINT

Strap joints are very common in practical applications, such as repairs, and are generally used when overlap joints are impractical due to substrate thickness. They are also used as a reinforcement method to increase the bonding area and reduce peel stresses. The use of thick belts, also known as straps, with tapered or bevelled ends, can further reduce peeling stresses.

5.1.3.6 SINGLE STRAP JOINT

A single strap joint is a type of butt joint in which only one cover plate is bonded on the main plate. This configuration allows for the increase of the contact surface for the butt joint and limits the peel forces exerted on the joint with respect to the 'strapped' side of the substrates.

This type of joint is subject to resisting bending and shear forces. The main weakness of this joint is the stresses of 90 degrees perpendicular to the substrate applied to the 'strapped' side of the joint.

FIGURE 109

Single strap joint

5.1.3.7 DOUBLE STRAP JOINT

A double strap joint uses two belts or straps to reinforce the joint. A strap is bonded to each side of the main substrate along the entire length of the bond. Not only does this type of joint make it possible to increase the bonded contact surface significantly, but it also greatly improves the mechanical and bending strength of the joint when compared to other joints. Though this is a very strong joint, aesthetic considerations may eliminate this joint from consideration.

FIGURE 110

Double strap joint

5.1.3.8 RECESSED DOUBLE STRAP JOINT

A recessed double strap joint is made by mechanically machining the joint ends and creating a butt connection reinforced by two straps or belts. It does not alter the joint dimensions but creates a larger bonding area and a better distribution of stresses. The processing or machining to achieve this joint configuration is complex; however, this joint provides high flexural strength and is well suited to handling a wide variety of stresses, including peel, shear and impact. This is one of the most effective joints that can be created with adhesives.

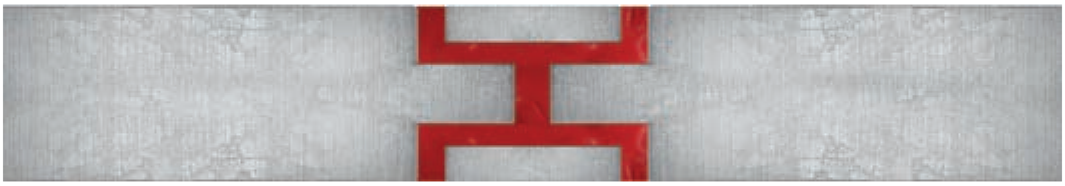


FIGURE 111

Recessed double strap

5.1.3.9 BEVELLED DOUBLE STRAP JOINT

Similar to the double strap joint, a bevelled double strap joint is made by adding a strap or belt to an adhesive bond line. The reinforcing straps will have a chamfer or bevel on both ends, which provides high flexural strength and better stress distribution. The critical function of the bevel is to prevent external assemblies from 'catching' the edge of the strap and applying peel forces. The mechanical processing required to create this joint is moderately complex. It should only be used if the bond is subject to materials sliding over the surface on the bonded substrates.

FIGURE 112

Bevelled double strap

5.1.3.10 OVERLAP JOINT

The overlap joint is the most commonly used adhesive joint. These joints are extremely simple, quick and easy to create, and are obtained by simply overlapping the components to be joined. This joint can be used with a wide variety of adhesives and substrate thicknesses. The major benefit of this joint is that it can bond extremely thin materials while providing excellent strength. This joint is strongest when forces are applied parallel to the substrates, but it also performs reasonably well when subjected to a variety of stresses. However, if an overlap joint is staggered and the shear forces are not aligned under very high stress loads, this can lead to substrate deformation, as shown in Section 4.

FIGURE 113

Overlap joint

5.1.3.11 JOGGLE LAP JOINT

The joggle lap joint is a simple method joint designed to address the shortcomings of the simple overlap joint. A properly implemented joggle lap joint will align loads, which will help prevent substrate deformation under high stress loads. The 'joggle' will also facilitate the joint assembly by providing a physical and visual indicator of where the bond line is to be situated. This type of joint can be made by simply bending the supports and requires minimal extra processing. This is the simplest and easiest-to-implement design for aligning loads.

FIGURE 114

Joggle lap joint

5.1.3.12 OVERLAP JOINT, TAPERED EDGES (BEVELLED LAP JOINT)

An overlap joint with tapered edges (bevelled lap joint) is more efficient than a simple lap joint because the bevelled edge, created by tapering the ends of the substrates allow for a more even distribution of load. This reduces the concentration of stress at the joint ends and prevents mechanical lifting due to external forces catching the substrate edge. This joint is also aesthetically more pleasing than a simple lap joint.

FIGURE 115

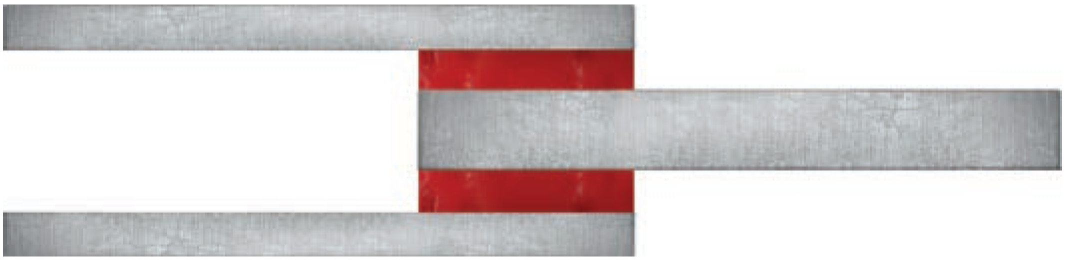
Overlap joint with tapered or bevelled edges

5.1.3.13 DOUBLE LAP JOINT

A double lap joint is a well-balanced joint consisting of two outer substrates, each bonded to a third central body. The central body is bonded on both sides. This joint is extremely effective when the central body is subjected to bending moments; it resists the stresses on the central body. If the external supports are subject to forces perpendicular to the substrate, there may be an increase in the stresses at the ends of the external bodies where the bond line meets the central body.

FIGURE 116

Double lap joint



5.1.4 NON-PLANAR SUBSTRATES

Mitigating stresses is more challenging when bonding with non-planar substrates. Angles created by non-planar substrates can lead to counterintuitive solutions, as the expected forces may not stress the joint as expected. It is important to choose the most suitable joint for the application based on the types of stresses acting on the bonded joints; in other words, forces and stresses should be considered first, with the joint designed around the expected forces and stresses. Particularly with right angles (90° angles), peel forces may impact the assembly in unanticipated areas. As discussed in Section 4, it is crucial to avoid peeling cleavage forces, as these are the most common forces that lead to failure. Figure 117 shows some of the most common peeling loads in non-planar assemblies and some possible design solutions to change the type of stress. This is not a comprehensive list, but rather a representative sample of the most common peel forces.

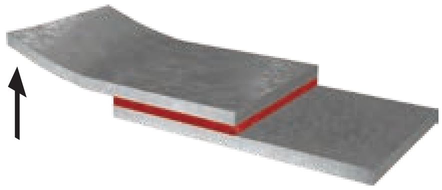
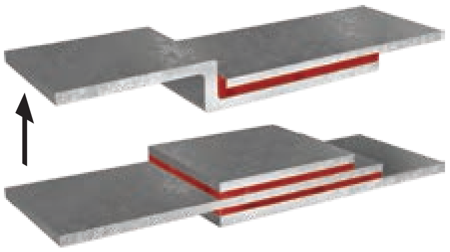
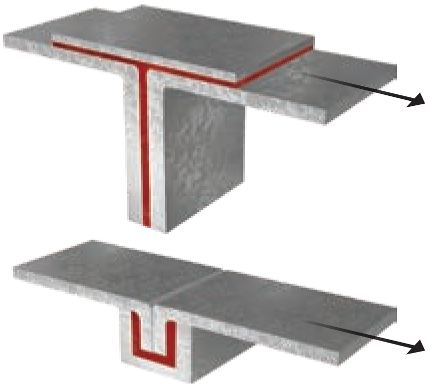
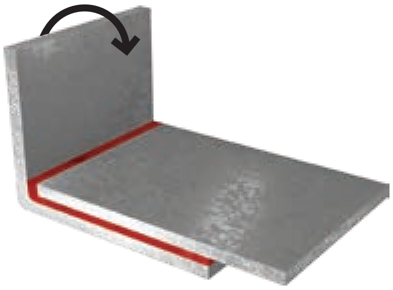
PEELING CLEAVAGE LOAD	POSSIBLE DESIGN SOLUTIONS
	
	
	

FIGURE 117

Peeling loads and their conversion by design measures

5.1.5 CYLINDRICAL SUBSTRATES

The bonding of cylindrical elements (rods) with a head-to-head or butt joint should be avoided due to the critical sensitivity to bending moments (peel/buckling). Much like planar substrates, cylindrical assemblies joined with this method are particularly weak.

This shortcoming may be overcome by utilising different geometries characterised by greater bending strength and greater extension of the bonded surface. As can be seen in Figure 118, a strong and effective joint requires engineering with geometries that allow stresses to be evenly distributed over the bond area. These examples are representative only and are not a comprehensive list.

An example of this joint in Figure 119 includes the bonding of needles in medical devices.

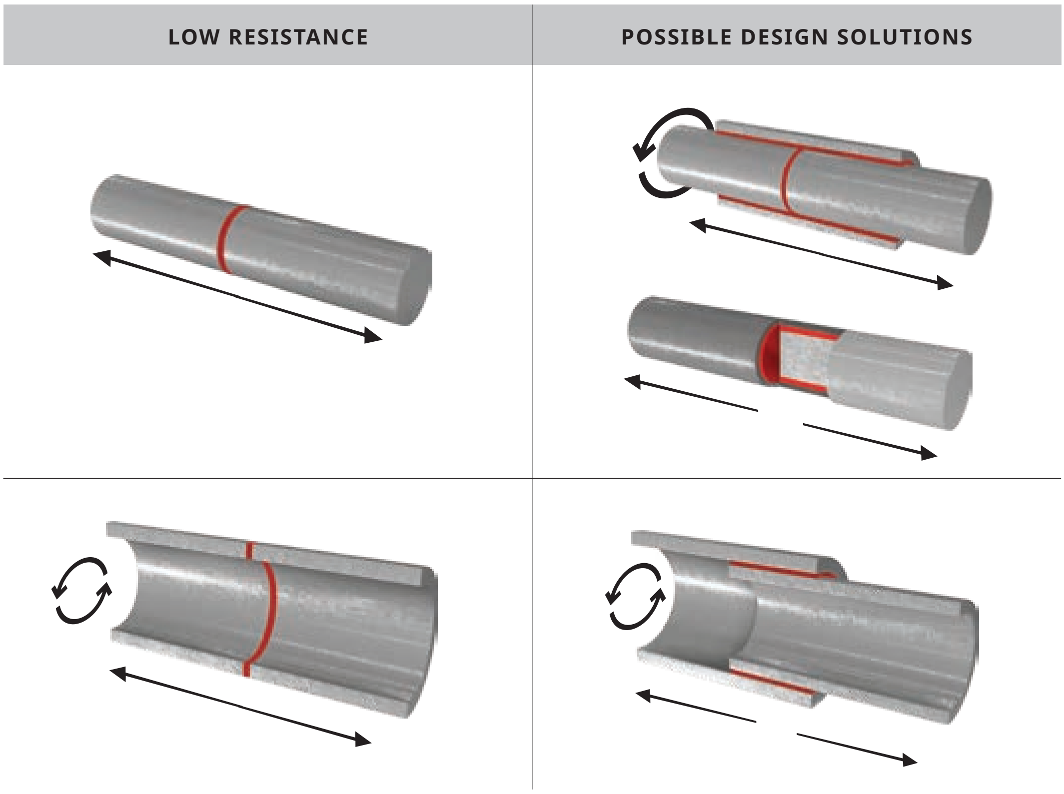


FIGURE 118

More or less favourable loads on joints. Better results are obtained with a larger bonding surface

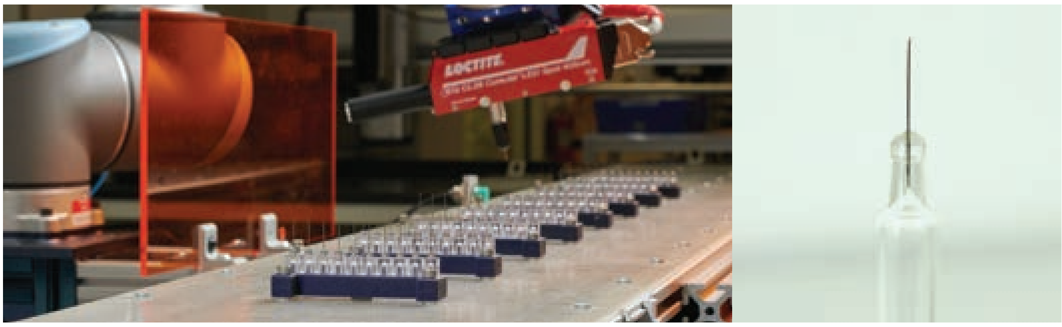


FIGURE 119

Examples of coaxial bonding between cylindrical parts

5.1.6 JOINTS WITH PLASTIC AND ELASTOMERIC SUBSTRATES

Compared to metals, plastic and elastomeric substrates are characterised by the following aspects:

- greater flexibility;
- lower modulus of elasticity;
- higher coefficient of thermal expansion; and
- anisotropy of physical/mechanical properties, meaning that the material may have different properties in different directions (i.e. directional grain structure).

These characteristics lead to a less even distribution of stresses in the adhesive layer, which is why flexible adhesives are generally recommended over rigid adhesives when bonding plastic and elastomeric substrates. However, the use of flexible adhesives is not always possible as they may limit the load capacity of the joint. The best compromise between load-bearing capacity and elasticity depends on the specific application and substrates.

5.1.7 JOINTS WITH THIN SUBSTRATES

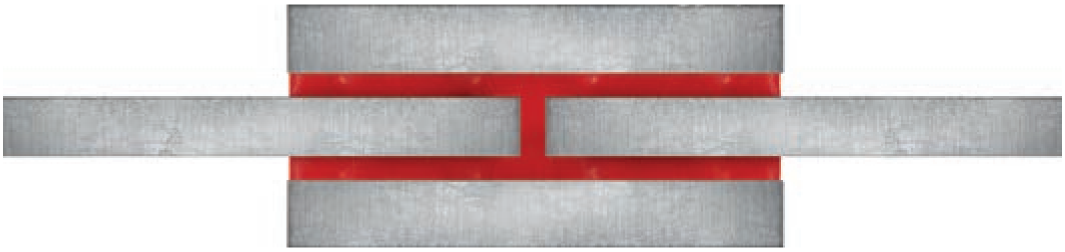
In general, thin substrates are bonded using simple overlapping joints or slightly modified joints. The double strap configuration is one of the most effective for this application.

For thin materials, two important considerations should be noted:

1. The material used for reinforcement, or straps, must be made of the same or similar material with equivalent strength, flexibility and thickness as the assembly substrate.
2. The adhesive should have the same degree of flexibility as the substrates or greater flexibility than the substrates.

FIGURE 120

Double strap joint with thin substrates



The thickness of the substrate is a very important variable for consideration. As the substrate thickness varies, so does the distribution of stresses within the joint and assembly; therefore, reinforcements to the joint may be required. As the thickness of the substrate decreases, the assembly will be more prone to peel forces. Conversely, as the thickness of the substrate increases, the assembly will be less prone to peeling forces.

If the substrate(s) depth is large enough, configurations with a scarf joint can be used; the appropriate thickness, where this becomes practical, will vary by substrate type. Ideally, the joint length (L) should be four times the size of the thickness (t) or greater.

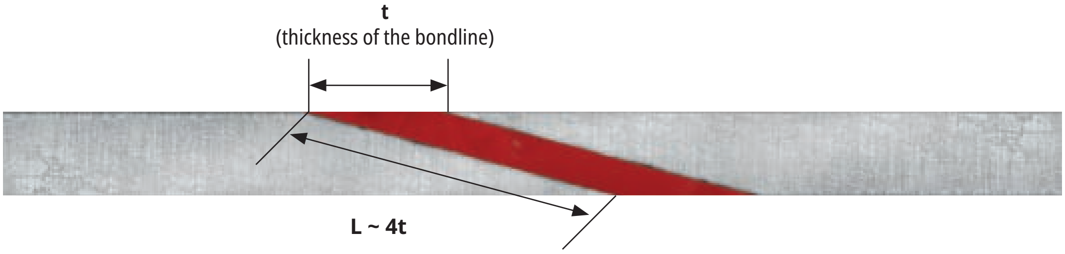


FIGURE 121

Ideal scarf joint sizing

Plastic matrix composites have physical and mechanical properties that depend on the direction in which the joint is made; this is referred to as **anisotropy**. The component should be designed so that the substrate is stressed in the preferred direction.

To avoid peeling forces when bonding thin or flexible substrates to metal:

- Avoid geometries with very acute angles to reduce excessive stress concentration.
- Increase the stiffness of the metal substrate to limit the occurrence of peel phenomena.

Adopt joint geometries that favour the stressing of the adhesive in its preferred direction (avoids peel).

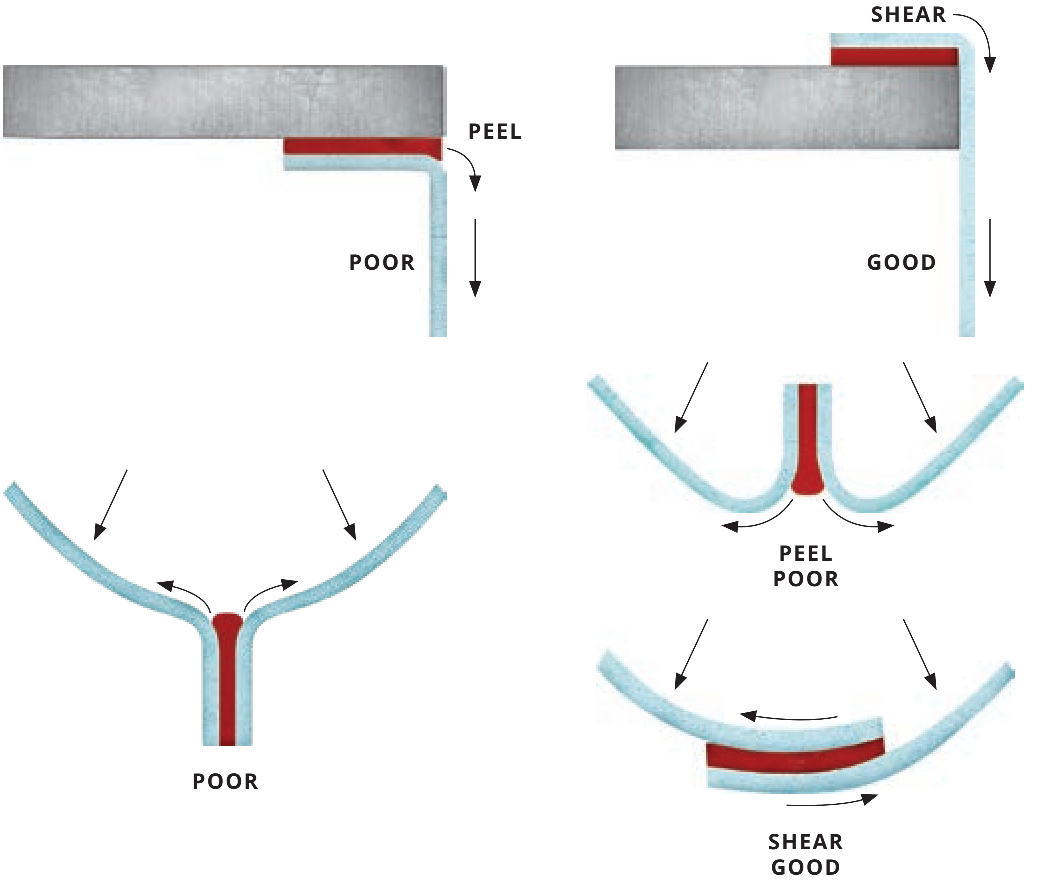


FIGURE 122

Typology of critical peeling joints and design suggestions

The final consideration is that it is important to limit the stresses on the substrate during the adhesive curing phase, as excessive clamping pressure may lead to residual stress at the interface.

5.2 GENERAL DESIGN GUIDELINES

The following guidelines should be used as overarching principles when designing a bond line within an assembly:

1. MAXIMISE SHEAR/MINIMISE PEEL AND CLEAVAGE

Note that from the stress distribution curve for cleavage and peel, these bonds do not resist stress very well. The stress is located at one end of the bond line. Whereas, in the case of shear, both ends of the bond resist the stress.

2. MAXIMISE COMPRESSION/MINIMISE TENSILE

Note that from the stress distribution curve for compression and tension, that stress was uniformly distributed across the bond. In most adhesive films, compressive strength is greater than the tensile strength. An adhesive joint that is feeling a compressive force is less likely to fail than a joint undergoing tension.

3. JOINT WIDTH IS MORE IMPORTANT THAN OVERLAP

Note that from the shear stress distribution curve (see Section 4), that the ends of the bond resist a greater amount of stress than does the middle of the bond. If the width of the bond is increased, the bond area at each end also increases; the overall result is a stronger joint. In this same overlap joint, if the overlapping length is greatly increased, there is little, if any, change in the bond strength. The contribution of the ends is not increased. The geometry of the ends has not changed; thus, their contribution to the bond strength has not changed.

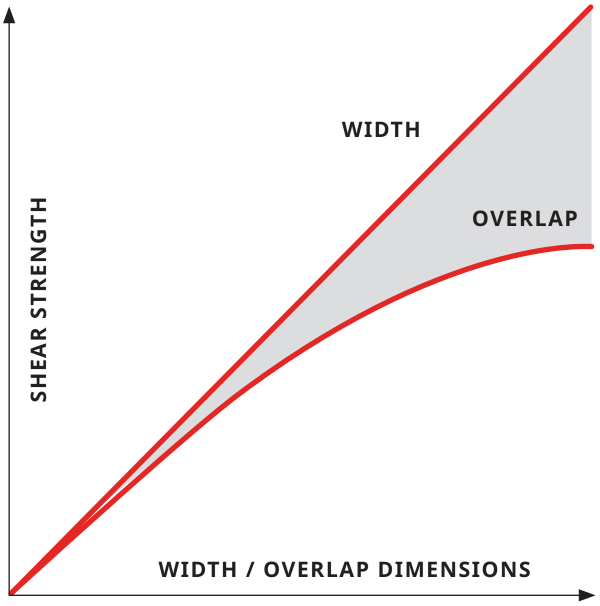


FIGURE 123

Bond shear strength width vs overlap. As a general rule, increase the joint width rather than the overlap area ('wider is better')

5.2.1

SUMMARY OF SUITABILITY OF COMMON BONDED JOINT TYPES

Table 17 summarises the main characteristics of common joints. In particular, the following are analysed:

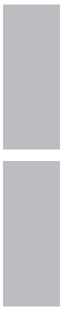
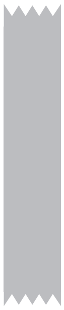
Self-alignment: The ability of the joint to arrange itself in the best position for bonding. Some joints are able to find and maintain the correct position on their own, while others require jigs or external fixturing to maintain the correct position during the bonding process.

Bond area: The total area available for bonding; the greater the area, the higher the joint strength.

Stress distribution: Depending on the type of joint, there will be a different distribution of stresses depending on the type of stress it must resist.

TABLE 17

Quick tips for choosing a joint

	JOINT					
	BUTT	**SCARF**	**STEPPED SCARF**	**STEPPED LAP**	**TONGUE & GROOVE**	**LAP**
						
Self-Alignment	None	None	Better	Better	Best	None
Bond Area	Poor	Better	Better	Better	Best	Good
Stress Distribution	Poor	Better	Better	Best	Best	Better

5.2.1.1 GAP REQUIREMENTS FOR BONDED ASSEMBLIES

Gap Effect in Rigid Adhesives

As a general rule, high modulus adhesives (rigid adhesives) possess high tensile strengths. Additionally, there is an inverse relationship between the bond line thickness and the tensile strength of adhesives. This is not an absolute rule; however, some adhesives require a specific gap to achieve maximum strength. Where this induced gap is critical; the adhesive will have spacer beads within the formulation and the gap will be specifically addressed in the (TDS) of the corresponding adhesive. This is most important during clamping operations as an induced gap relates to the overall clamp force applied to the assembly; care should be taken not to apply too much force, as this may cause the spacers to be crushed or displaced and the induced gap will be less than specified, resulting in a lower strength bond than desired.

If an induced gap is not specifically advised, using rigid adhesives with thin gaps is usually recommended as long as the bond-line gap is fully filled. Thicker gaps normally result in lower assembly strength because cleavage forces more readily occur due to nonaxial loading or internal stresses in the adhesive.

The most important aspects of the adhesive gap or bond-line thickness for rigid adhesives are magnitude and uniformity, or homogeneity. Generally, it is important to have as thin an adhesive layer as possible without any chance of insufficient coverage. When using rigid adhesives, bond line thicknesses or gaps from 0.02 mm (0.001 in) to 0.20 mm (0.008 in) are recommended, as data show that adhesive strengths do not vary significantly in this range. The optimal bond line thickness is about 0.1 mm (0.004 in), though with thicker adhesive bond lines, there is a higher risk of incorporating voids into the joint. Stresses at the corner of the adhesive/substrate tend to be larger in large gaps, as it is difficult to keep the axial loads aligned (see Joggle Lap Joint, Section 5.1.3) with a very thick bond line.

High modulus, or rigid, adhesives are generally formulated to cure in thin sections. Thicker sections may alter the curing properties, prevent the adhesive from fully curing and result in increased internal stresses due to shrinkage or exotherm during the cure.

The gap should be as uniform as possible, which equates to the substrates being as parallel as possible; by maintaining uniformity in adhesive thickness across the bonded area, strength and stress distribution will be maximised. If the adhesive gap is not uniform, the axial loading will not remain aligned, subsequently translating into cleavage stress on the adhesive.

Several methods may be employed to ensure consistent and correct gaps in the adhesive joint. These include the following:

- Application of pre-calculated pressure (clamp load) during cure.
- Use of fixturing that is specifically designed for the application.
- Application of a shim or insert within the bond line so that a uniform, predetermined thickness can be maintained.
- Use of an adhesive that has spacer beads incorporated into the formulation.

A comparative test was carried out between a two-step, no-mix acrylic adhesive and a 1C epoxy adhesive to evaluate the strengths obtained after curing at various adhesive gaps. The tests were performed using a non-standard joint designed for torque measurements (Figure 124) and according to ASTM D1002-01 to measure tensile shear values (Figure 125). The results of the torque test component are summarised in Table 18.

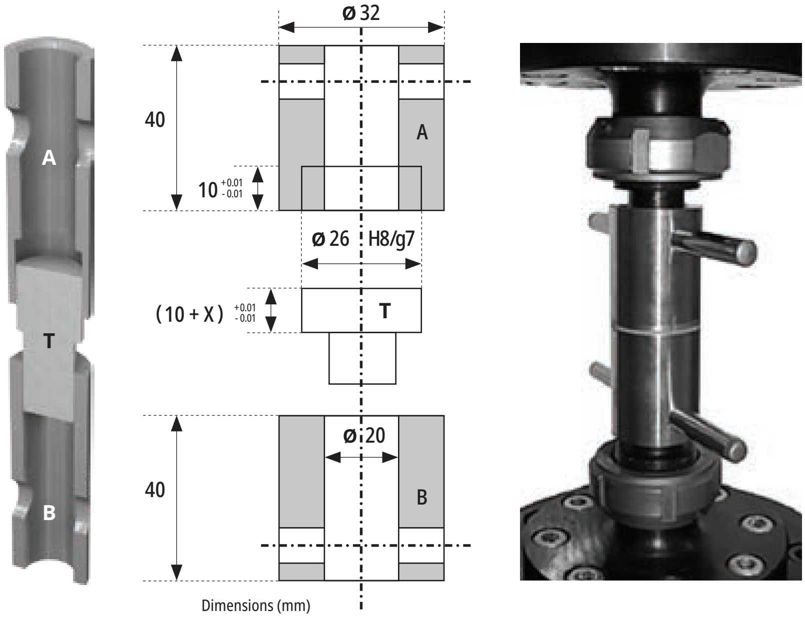


FIGURE 124

Joint used for experimental tests. Refer to Table 18 for data

TABLE 18

Variation of torque as the gap changes

BOND LINE THICKNESS (mm)		0.05	0.1	0.2	0.4
2-STEP ACRYLIC ADHESIVE	Peak torque (Nm)	73	62	43	30
		98	81	21	16
		79	74	36	22
		65	64	47	20
		68	66	49	28
	Average peak torque (Nm)	**77**	**69**	**39**	**23**
	Standard deviation (Nm)	**13**	**8**	**11**	**6**
1C HEAT CURING EPOXY	Peak torque (Nm)	190	195	187	172
		172	186	190	176
		181	204	182	162
		199	187	200	177
		166	204	190	184
	Average peak torque (Nm)	**181**	**195**	**190**	**174**
	Standard deviation (Nm)	**13**	**9**	**7**	**8**

An evaluation of the same behaviour with a tensile lap shear test, according to ASTM D1002-01, yielded the values summarised in Table 19.

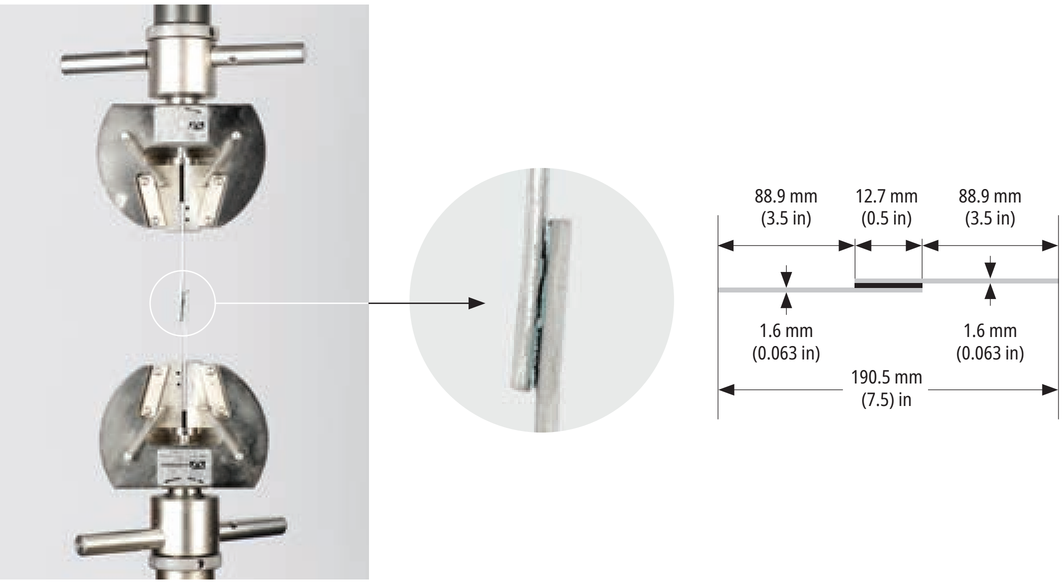


FIGURE 125

Joint used for experimental tests according to ASTM D1002-01 (dimensions in mm). Refer to Table 19 for data

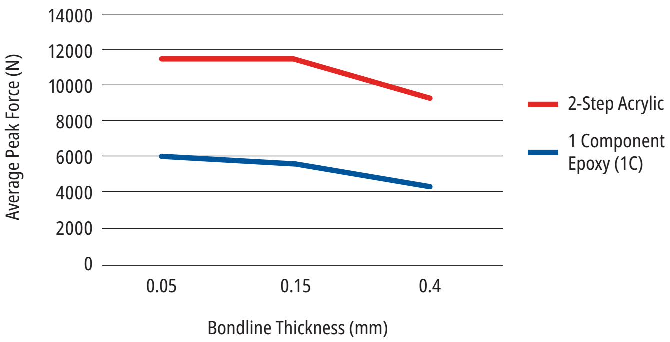
TABLE 19

Force values obtained as the gap varies

BOND LINE THICKNESS mm (in)		**0.05 (0.002 in)**	**0.15 (0.006 in)**	**0.4 (0.016 in)**
2-STEP ACRYLIC ADHESIVE	Peak force (N)	5,396	6,033	3,499
		6,104	5,326	4,350
		6,036	5,336	3,993
		5,649	5,761	4,550
		6,579	5,696	5,353
	Average peak force (N)	**5,953**	**5,630**	**4,349**
	Standard deviation (N)	**454**	**301**	**688**
1C HEAT CURING EPOXY	Peak force (N)	12,434	10,248	9,359
		12,019	11,677	10,024
		10,579	11,776	9,026
		11,275	12,537	9,276
		10,986	11,328	9,160
	Average peak force (N)	**11,459**	**11,513**	**9,369**
	Standard deviation (N)	**758**	**833**	**387**

FIGURE 126

Tensile lap shear average peak force over varying bond line thickness



The results obtained in Tables 18 and 19 show how the strength of rigid adhesives varies with the thickness of the adhesive applied. In Table 18, the torque clearly decreases with increasing thickness for a two-step no-mix acrylic, while it has a less significant impact on the torque strength for a 1C heat curing epoxy. Table 19 shows how the performance of both products decreases as the adhesive thickness increases.

These data show how important it is to apply the correct thickness of adhesive to achieve the maximum desired performance.

5.2.1.2 SUBSTRATE PROPERTIES AND JOINT PERFORMANCE

Following the performance of the adhesive, the second considerations that must be accounted for when designing and testing a joint are the specifications and properties of the substrates. Even the most well-designed adhesive assembly designed to accommodate all expected forces will fail if the substrate is not fit for the purpose.

The following properties are the most common factors to consider and they may individually or collectively determine whether the use of a particular adhesive will be successful in an application in the short and long term:

- Flexibility
- Hardness
- Thickness of a substrate
- UV resistance
- Moisture resistance
- Thermal expansion/contraction
- Thermal tolerance
- Chemical resistance
- Anisotropic/Isotropic
- Impact resistance

5.2.1.3 SUBSTRATE FLEXIBILITY

In general, many adhesives will have properties relating to flexibility listed in the technical literature, such as TDS or material specification sheets. The flexibility of cured adhesives will usually be characterised by Young's modulus (also referred to as the elastic modulus), elongation before break and Poisson's ratio. In general, there is a trade-off between shear strength performance and elongation, as seen in Figure 127. Engineers must be aware of this relationship when they match the flexibility of the adhesive to the requirements of the surfaces being assembled. Just like solid materials, cured adhesives have flexibility and strength properties that vary by polymer chemistry. Generalised expected properties by chemistry are shown in Figure 127. In many cases, matching the flexibility of the adhesive to the substrate (Figure 128) is ideal. In other cases, a high-strength, rigid bond is required to provide the best structural integrity.

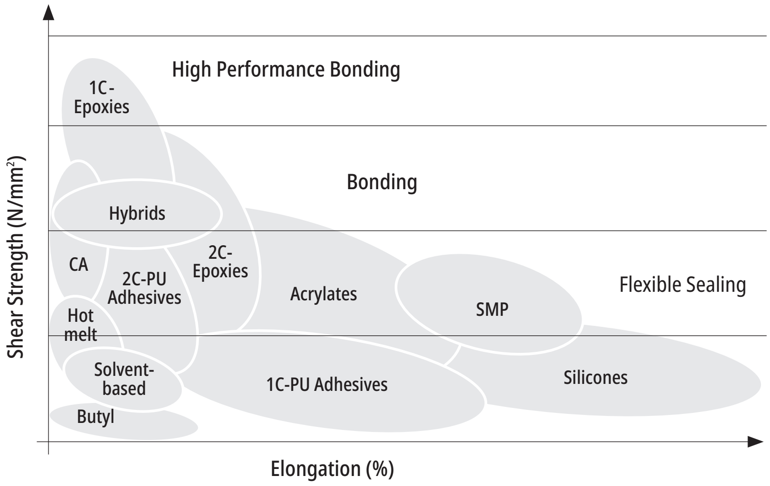


FIGURE 127

Flexibility of adhesives

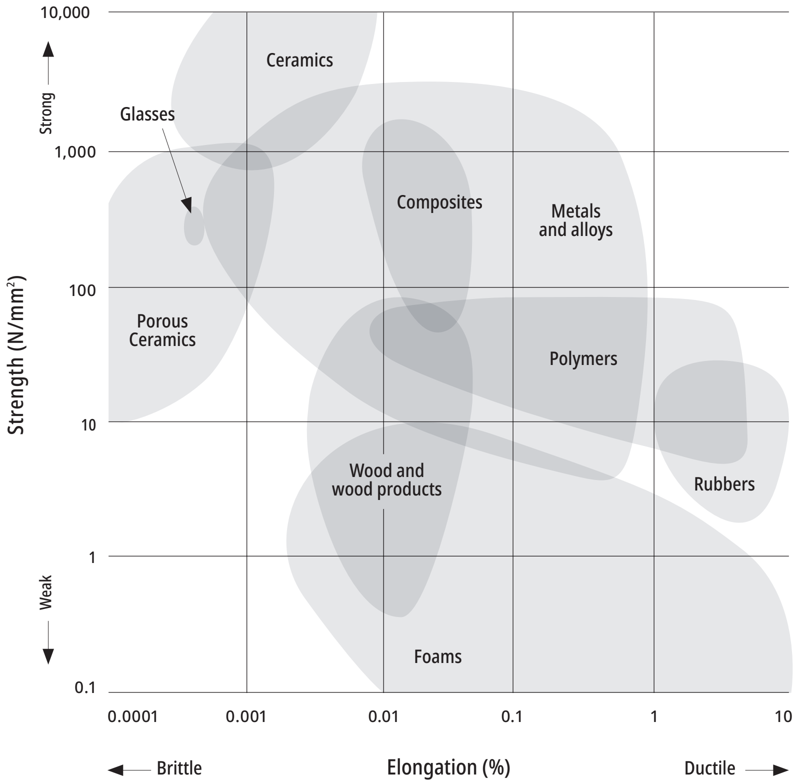


FIGURE 128

Strength vs elongation for solid materials

All solid materials will also exhibit many of the same properties as cured adhesive. The flexibility specification of many common materials is available in online databases or is readily available from manufacturers. In most cases, adhesives are more flexible, with a much lower Young's modulus, than the materials to which they are bonded. However, adhesives are sometimes used to stiffen thin, flexible substrates in conjunction with a solid composite 'honeycomb'.

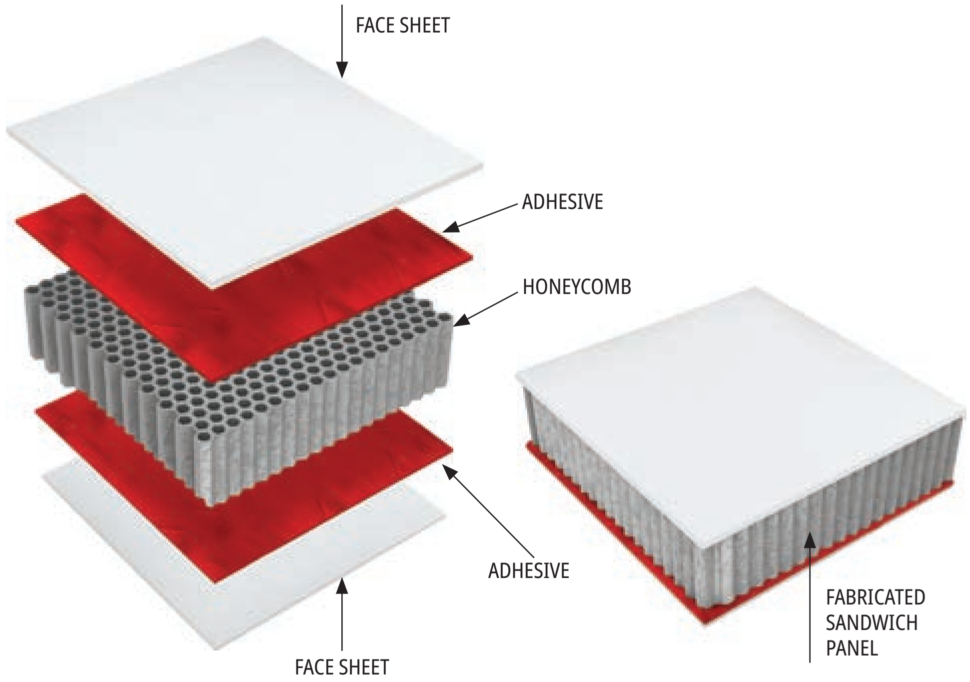


FIGURE 129

An example of where an adhesive may be used to construct a material and improve the strength of a thin composite, to produce a better strength-to-weight ratio

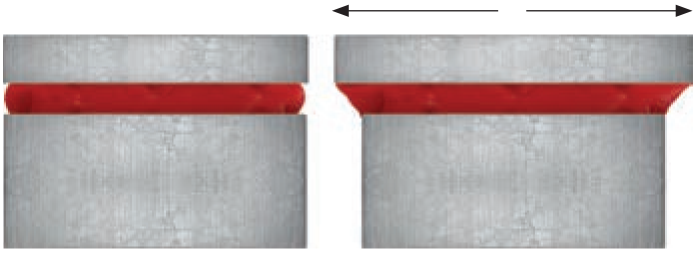
Depending on the expected static or dynamic loads to which an assembly might be subjected, it may be necessary to use a more flexible adhesive to accommodate microscopic displacements of surfaces, which may lead to cracks/failure in more brittle substrates. A common misconception is that a higher frequency or magnitude of dynamic loads should be addressed by selecting adhesives with higher shear strengths, when, in many instances, high magnitude or frequency dynamic loads are more suited to flexible adhesives. This phenomenon is due to the ability of a flexible adhesive to absorb and flex with dynamic loads, whereas higher strength adhesives will not flex, which may lead to substrate or joint fatigue over time. On the one hand, assemblies with high vibration may need a more flexible adhesive to absorb energy without failing. On the other hand, a high-strength product would provide a higher adhesive strength but would not have the ability to absorb energy or accommodate movements and may become fatigued or cause unnecessary stress in the substrate. The flexibility of the adhesive, and its ability to absorb energy, is particularly important when engineering joints with materials that may become work-hardened, such as aluminium.

5.2.1.4 SUBSTRATE THERMAL EXPANSION AND CONTRACTION

Substrates are also subject to microscopic movements during thermal expansion and contraction, which may cause adhesive bonds to fail if substrates and adhesives are incorrectly paired. One of the greatest advantages of adhesives is their ability to join dissimilar materials with ease. However, since all materials will expand or contract at different rates, an adhesive should be paired with the assembly that is able to expand and contract with the substrates (similar coefficient of thermal expansion) or is flexible enough to accommodate the differential expansion and contraction of the substrate.

FIGURE 130

An exaggeration of the coefficient of thermal expansion differential when dissimilar substrates are bonded together. The adhesive (shown in red) must be able to allow for this expansion without failing. In this case, a flexible adhesive is desirable



Compensation of differential material expansion

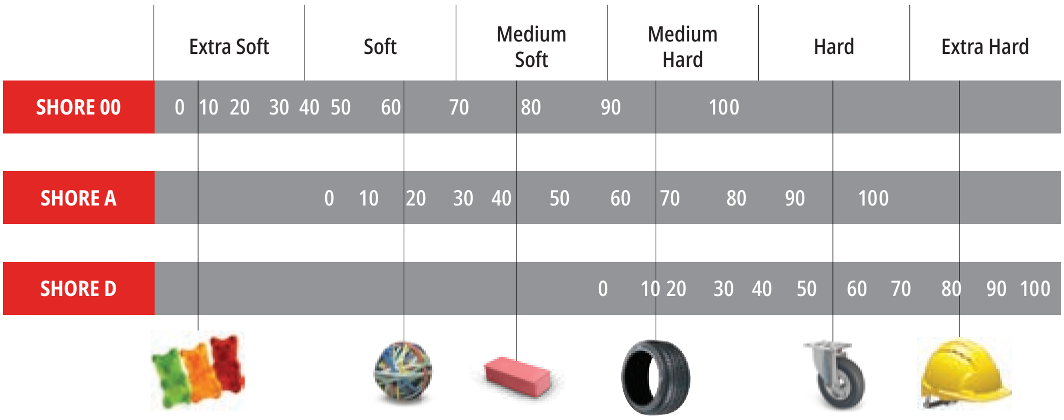
For example, if we consider two one-metre beams, one made of steel and one made of aluminium, using principles and coefficients of linear thermal expansion, a temperature swing from 20°C (68°F) to 140°C (284°F) will cause the steel to expand 1.3 mm (0.05 in), while the aluminium would expand at a greater rate with a temperature of 2.8 mm (0.11 in) past the original one-metre length. Therefore, many adhesive properties have become relevant in creating a design that accounts for different rates of expansion. Assuming the direction of expansion is along the long axis, the adhesive must be able to withstand tensile load (see Section 4) as the forces applied are pushing/pulling the substrates relative to one another. If the adhesive is not sufficiently flexible or able to withstand the tensile load, the bond will fail.

5.2.1.5 SUBSTRATE HARDNESS

Also referred to as 'durometer', hardness is measured empirically by observing how far a spiked probe extends into a surface. This property is usually correlated with the flexibility of a material. In some instances, it may be better for the durometer of the adhesive to be much lower than the substrates, such as in a compressed silicone gasket on a rigid flange. The Shore scales of hardness are the most common method of quantifying this property. Table 20 shows the different Shore scales with examples of materials that fall into these ranges.

TABLE 20

This chart illustrates how the Shore hardness scales relate to each other. These three Shore scales are the most commonly used to measure the hardness of adhesives



Most adhesives will be measured in the Shore A or Shore D scales; however, there is overlap between the scales of hardness. For example, a high rating on the Shore A scale could be the same as a low rating on the Shore D scale. When comparing multiple materials, it is always best to use the same Shore hardness scale and the same testing equipment if possible.

5.2.1.6 THICKNESS

The thickness of the substrate may also be indicative of the interaction between the substrates and the adhesives. Even a material with a high modulus (i.e. rigid materials like aluminium) can become very flexible in thin films or sheets. A good example is aluminium foil commonly used for cooking. It is easily folded or torn by hand, compared to a thick plate or sheet of aluminium, which requires mechanical force to fold or tear. Differences in test data and the real world may at times be explained by this property, as real-world test data on thinner or thicker substrates may differ from the numbers provided in technical literature such as the TDS (which is calculated using standard dimension substrates).

For example, thinner substrates will sometimes induce different failure modes, commonly transforming a shear or tensile adhesion failure into a peel failure, as the thin substrate deforms. Another failure mode that can occur in testing with thin materials is substrate failure, in which a test specimen fails before the adhesive joint due to insufficient substrate thickness. While substrate failure can be a desirable failure mode because it confirms the ability of an adhesive to outperform the material it is bonding, data from materials property testing will reflect the strength of the substrate and not necessarily the adhesive.

FIGURE 131

For these assemblies, one joint is bonded and one joint is bolted. When the strengths of the assemblies were tested by pulling them in tensile load, the material started to fail first around the bolted joints. In this case, the assembly experienced substrate failure

The flexibility of the substrate as it decreases in thickness is prevalent when comparing rigid flanges and stamped flanges, both of which are sealed by compressing an elastomeric adhesive and which may lose their ability to form a reliable seal if the flange material, in this particular case a rigid flange (cast metal), is too thin. An excess clamp load on the stamped flange may lead to deformation, allowing a leak path. A rigid flange (cast metal) generally does not see this issue. Flexibility as it relates to material thickness explains why stamped parts have greater stress concentrations than thicker machined flanges.

FIGURE 132

An example showcasing the importance of substrate thickness. The photo shows a housing with a cured silicone gasket around the edges

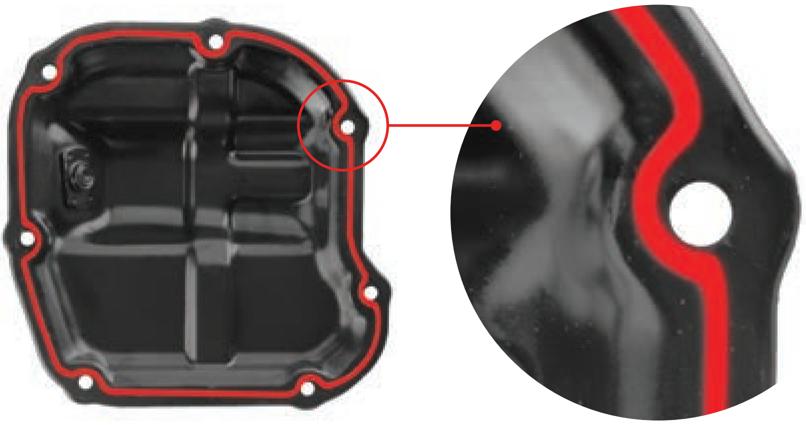
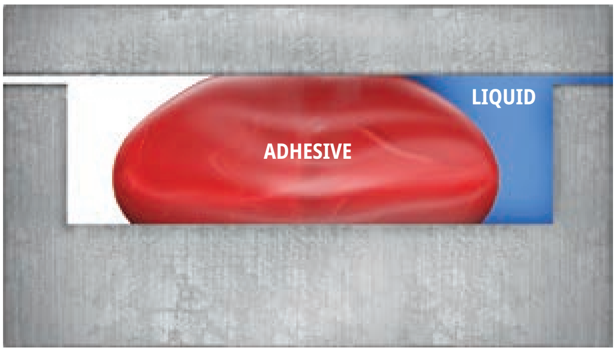


FIGURE 133

Since this gasket needs to be compressed to form a seal, as shown on the right-hand side, it is important that the substrate maintains rigidity



5.2.1.7 SURFACE ENERGY

The surface energy of the substrates should be a primary consideration when choosing a bonded assembly. For a comprehensive review of surface energy and polarity, see Section 4.

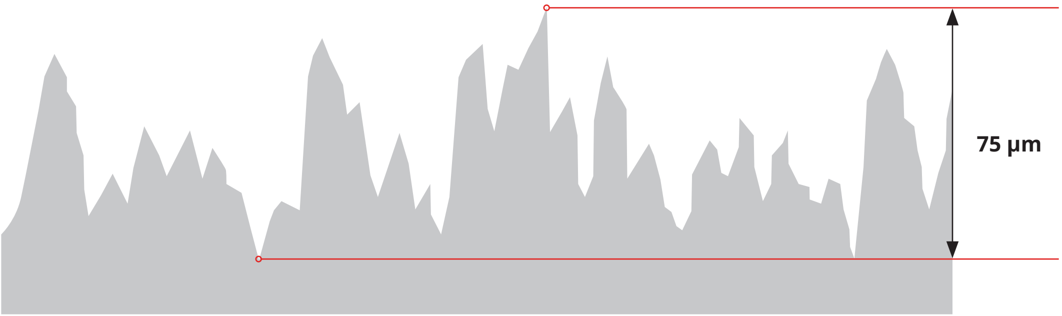
5.2.1.8 SURFACE ROUGHNESS

Surface roughness is another property that can affect not only the ability of an adhesive to wet to a surface but also the adhesion properties of the assembly. One example of manipulating a surface's roughness for better adhesion is the recommended preparation procedure. It is recommended (when possible) that shot blasting be used not only to knock any loose material away from the surface before performing the repair but also to effectively increase the surface area the floor repair products will have to bond to, thereby increasing the adhesion.

The same principle can be used for many chemistries, which is why an adhesive product's TDS will include shear adhesion results for metal substrates that have been grit blasted. Typically, the roughness of a surface is measured in a unit of length, which represents the average height between the peaks and valleys on the roughened surface (Ra). In general, surface roughness is determined by the manufacturing processes used to produce materials as well as preparation steps such as sanding or grit blasting. Therefore, this profile will vary. Figure 134 shows a 75-micron surface roughness profile typical of a grit-blasting preparation step. Note that there is no general rule of thumb for surface roughness when preparing a surface for bonding since the interaction between the roughness and the adhesive will also be affected by the surface tension or by the ability of the adhesive to flow into the microscopic peaks and valleys to form a good bond.

FIGURE 134

Surface roughness is the average distance between the microscopic peaks and valleys in the structure of a material. Even surfaces that appear smooth to the human eye have some form of roughness



5.2.1.9 SURFACE POROSITY

Surface porosity is important because it can affect not only the surface energy and roughness causing changes in the adhesive placement and adhesion, but also the long-term reliability and performance of an adhesive joint. By definition, porous solids allow liquids or gases to permeate throughout. Therefore, if a porous material is bonded, it may absorb substances that can potentially harm the integrity of the bond. For example, plywood laminated with an adhesive may absorb moisture after being exposed to environmental conditions, which may lead to delamination. Therefore, it would be prudent to select an adhesive that resists moisture, seals porous material and prevents the absorption of moisture; or alternatively, change the design. Another reason to be cautious is that some porous materials may come with additives that leach out of the surface over time. This is of particular concern with certain plastics and rubbers that leach oil as they age.

5.2.1.10 CLEANLINESS

Arguably, the most important consideration of all is the cleanliness of a surface before bonding. Even with proper surface energy, surface roughness and other preparation steps, a contaminated surface will severely hinder the ability of an adhesive to perform properly because adhesives only form bonds with the very top layers of the surfaces to which they bond. Therefore, if the surface of a material is 50% contaminated with fingerprint oils, you could expect to get 50% or less of the performance you would get on a clean surface. In this case, fingerprint oils act as a release agent, providing no adhesive performance at the locations of contamination. Consider the graphic below and the different types of adhesion.

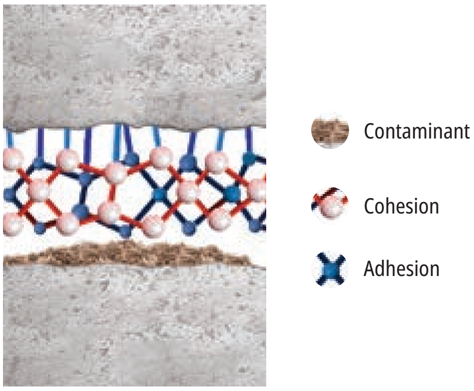


FIGURE 135

Adhesion occurs only at the interface of the adhesive and the material occupying the top layer of a substrate. This graphic illustrates how imperfect cleaning may lead to surface contamination and decreased adhesion

As an adhesive cures, it polymerises and bonds to itself, and it forms bonds to the top layer of the surface with which it is in contact. If this layer is contaminated with oil, grit, dust or any other substance, the adhesive is blocked from forming a sufficient bond. Both water-based and solvent-based cleaners can be used to ensure a clean surface before a bond. The general benefit of a water-based cleaner is that it can remove salt contaminants as well as greases and oils. While solvent-based cleaners rarely have the ability to remove salts, they are very effective degreasers, and they rarely leave residue on surfaces. Greases and salts are not the only substances that commonly contaminate bonding surfaces. Parts that come from other manufacturing processes, such as machining, may be covered in cutting fluid or machining coolant. Injection moulded plastics may be covered in a release agent which would render an adhesive less efficient. Steel and other oxidising metals sometimes come with a protective film of oil. It is important to note that certain types of contamination may affect the ability of certain adhesives to cure. Two examples of this are pH and nitrite contamination. Changes in the pH levels caused by salts on surfaces can severely hinder the cure of certain types of adhesives like Cyanoacrylates, which depend on basic or neutral surfaces to start the breakdown of acidic stabilisers in the formulation. Nitrite salts are commonly left on metal surfaces after machining processes and can hinder the ability of anaerobic adhesives to polymerise. In both cases, the use of water-based cleaners can be used to remove the salts and ensure proper adhesive performance.

Since adhesives only bond to the top surface of a material, there is a misconception that adhesion data listed on the TDS for certain materials will also apply if there is a coating. In reality, the performance of the adhesive is more accurately predicted if one considers the chemical composition of a coating. For example, if a steel panel is being bonded but is covered with a protective urethane-based coating, then any technical information on adhesion to urethane would be more applicable. In some cases, such as the automotive repair industry, a protective coating can be removed at the location of the bond surface to ensure maximum performance, since adhesives can sometimes perform better on the base material and not the coating. The adhesion of the coating to the base material should also be considered when designing a bonded joint. Just as when substrate failure occurs, a lower adhesion test result can be the product of delamination of a coating to a material and does not necessarily reflect on the performance of the adhesive.

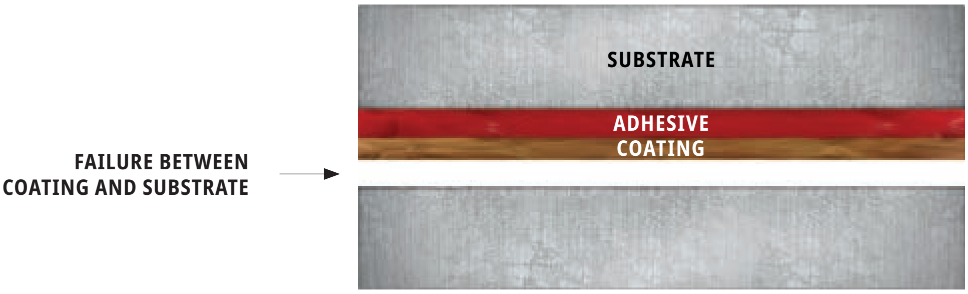


FIGURE 136

Adhesive (red) has bonded to the coating (brown) and one substrate; however, the coating has failed at the interface between the coating and the substrate

5.2.1.11 CALCULATING STRENGTH IN BONDED ASSEMBLIES

No matter the application, industry, material or adhesive, engineers and technicians are always asking a simple question: How will we know an adhesive is strong enough? In a world where many mechanical assembly methods are being replaced with chemical adhesive bonding, ensuring the strength, safety and reliability of a finished assembly is of the utmost importance. There are as many ways of testing strength as there are assembled parts, ranging from pull-out strength tests on bonded medical needles to head-on crash testing of automobiles in windscreen bonding applications. Different failure modes can also be tested. For example, peel strength may be more important than tensile or shear strength in a highly flexible assembly. Another example is that impact resistance might be the most important factor for a structural adhesive used to bond body panels on a vehicle.

FIGURE 137

One of the best examples of adhesive qualification in the window glazing industry is crash testing. Since windscreen bonding adhesives play an important role in safety, it is important that this type of testing is conducted prior to widespread use

It is ultimately up to design and production engineers to determine a test metric that best correlates to the real-world performance of their product, and thankfully there are many industry test methods and standards to help guide that process. These test methods are usually performed during both the design process (adhesive qualification testing) and production (quality control tests). Quality control engineers and technicians must be careful not to test products before the adhesive has had sufficient time to cure, lest the results of that test misrepresent the performance of the adhesive and the assembly. While simulated testing is the most accurate way to assess the strength of bonded assemblies, there are some methods for approximating bond strength.

Calculating estimated bond strength goes back to one of the most basic principles of adhesives: stress distribution. Traditional assembly methods, including rivets, nuts and bolts, spotwelds and clamps, tend to concentrate the load-bearing interface of the parts in a very small surface area, leading to stress points which are usually the points of failure for an assembly (see Section 4). Alternatively, using adhesives distributes the load over a larger surface area, allowing the assembly to withstand greater loads.

The larger the surface area, the lower the stress. Consider the following equation for the shear stress of a joint, where σ is the stress, A is the surface area of the bond and F is the force of an external load.

$$\sigma = \frac{F}{A}$$

Assuming that the stress is equal over the entire surface area, there is a proportional relationship between the force and the stress in the bond line and an inversely proportional relationship between stress and surface area. Since failure occurs when σ exceeds the yield stress of the bond itself, engineers should design assemblies to minimise this stress. Therefore, either the applied force must be minimised, the surface area must be maximised, or both. In most applications, controlling the forces or external conditions experienced by an assembly is not possible. For example, engineers cannot control stress in the automotive windscreen bond line when collisions occur. However, engineers can design the interface of the windscreen and the car body panels to maximise surface area. Therefore, a maximised surface area is directly related to maximised adhesive performance.

FIGURE 138

A bonded assembly is tested for shear strength in accordance with ISO 4587. The results of this test method are commonly listed on TDS

The information available on the TDS will vary depending on the product. However, the most common test result included will be shear strength, which also happens to be one of the most popular methods for evaluating adhesive performance, following ISO 4587.(14) While shear strength is usually a good indicator of how well an adhesive will bond to the surface of a material, it may not necessarily be an indicator of performance. For this reason, engineers should pay close attention to the differences in the predicted (calculated based on surface area) and observed strength.

In fact, many factors can cause differences in the observed strength results versus the calculated results. Thinking about surface cleanliness, the top surface may be contaminated or simply covered in a protective coating such as a powder coat or paint system. Furthermore, even the same material listed on the TDS may have different adhesion depending on the grade, alloy, blend or even manufacturing batch. For these reasons, rough calculations based on technical data may be a good starting point for selecting an adhesive, but the best practice is to always perform testing to verify the level of performance in the conditions that are most relevant to the integrity of the assembly. Later sections will provide more insights into how observed testing results may be interpreted.

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14) International Organization for Standardization, 'ISO 4587 Adhesives - Determination of Tensile Lap-Shear Strength of High Strength Adhesive Bonds,' 2003.

5.2.2 FACTORS FOR BOND LINE AND ASSEMBLY STRENGTH

Calculating the bond line or assembly strength is a complicated yet essential step in the validation of an adhesive for a specified application. Documents such as TDS, white papers and adhesive/chemistry specifications will contain adhesive properties, benefits and limitations, specific substrate bond strengths, end user-specific requirements and real application testing data. The starting point for any assembly strength calculation or assessment should be the relevant technical literature provided.

5.2.2.1 TECHNICAL DATA SHEETS (TDS) AND TEST DATA

A product-specific TDS is a technical document containing the product description and some basic facts about the product, uncured and cured characteristics of the adhesive, general information on surface preparation and recommended application methods. The TDS will also provide product-specific technical information, test data regarding the performance of cured adhesives on common substrates and environmental resistance data. The American Society for Testing and Materials (ASTM) standards or International Organization for Standardization (ISO) test methods associated with the test data are commonly provided. The data published on the TDS is gathered using production batches to ensure it is as applicable as possible to real-world applications.

When trying to determine suitable adhesives and sealants, a product TDS is a great resource to gain an understanding of the product’s benefits and limitations; typically, these will be listed as hardness, shear strength, elongation at break, chemical resistance and temperature resistance. Data relating to adhesive performance when cured has been measured under specified conditions (such as temperature and humidity), which are typically listed on the TDS.

Bond strength data are typically listed in [N/mm^2] and [psi] and in the 'Typical Performance of Cured Material' section. Physical properties of the cured adhesive under specified conditions, independent of substrate, are also listed; these include shore hardness, elongation, tensile strength and other physical test data where applicable. The specific data listed on a TDS will vary by adhesive type and chemistry; however, the most important characteristics of a specified adhesive or chemistry will always be included. This section also contains cured bond strength data as it relates to various common or representative substrates; again, these data are measured under standardised curing and testing conditions which are typically listed on the TDS.

Bond strength data are gathered based on standardised test methods such as ASTM, ISO and DIN depending on the type of stress the bond is exposed to. The specifications of test procedures, such as repetitions, temperature and substrate type, are typically specified in the standard test method documentation. The majority of the reliable adhesive joint strength tests fall into four categories: tensile, shear, and peel and compression.(15)

An analysis of the TDS of the adhesive will provide a starting point for conducting preliminary trials under production conditions. While laboratory testing may help validate adhesives in a specific application, these production trials are an essential step before a final decision can be reached.(16)

When relying on TDS information, it is important to remember that many of the characteristics listed on the data sheet may be affected by multiple factors such as cure time, substrate type, surface preparation methods, bond line gap, bond area, application temperature and relative humidity (see Section 4). It is absolutely critical to understand that real-world production or maintenance conditions may not always match the controlled conditions under which the adhesive has been cured and tested.

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15) A. Pizzi, and K. L. Mittal. *Handbook of Adhesive Technology,* M. Dekker, 2003.

16) Loctite North America. *Worldwide Design Handbook.* Rocky Hill: Loctite European Group and Loctite North America, 1998.

5.2.3 ADHESIVE CHEMICAL-SPECIFIC PROPERTIES

The adhesion, cohesion and overall strength of bonded assemblies can vary depending on the chemistry of the adhesive product and the specific chemicals that the cured adhesive is subjected to over the life span of the assembly. Each specific chemistry or technology has its respective benefits and considerations that should be considered, especially when selecting an adhesive for an application that will be subjected to specific chemicals. Although adhesives and sealants are often formulated from the same types of base materials, they are specifically engineered to have different properties; therefore, each adhesive should be evaluated individually based on its specific properties.

As Table 21 shows, there are a large number of technologies, which each have specific benefits and considerations, and with each chemistry having typical representative characteristics. This is a high-level overview; each chemistry is covered in depth in the following section.

TABLE 21

Summary of general representative characteristics of specific adhesive chemistries

PERFORMANCE CONSIDERATIONS	ADHESIVE CATEGORY				
	Elastomers	Urethanes	2C Acrylics	2-Step Acrylics	Hybrids
Advantages	Flexible, paintable, bonder/sealant	Excellent toughness, flexibility	Good impact resistance, flexibility	Good impact resistance, no-mix	Universal adhesion, Fast fixture through high gap
Considerations	Limited temperature resistance	Sensitive to moisture	Mixing required	Primer required	Mixing require
TEMPERATURE RESISTANCE					
Typical for the category	-54°C to 93°C (-65°F to 200°F)	-54°C to 121°C (-65°F to 250°F)	-54°C to 121°C (-65°F to 250°F)	-54°C to 149°C (-65°F to 300°F)	-40°C to 100°C (-40°F to 210°F)
Highest Rated Product	93°C (200°F)	149°C (300°F)	121°C (250°F)	204°C (400°F)	150°C (300°F)
ENVIRONMENTAL RESISTANCE					
Polar solvents	Good	Good	Good	Good	Very Good
Non-polar solvents	Poor	Good	Very Good	Very Good	Very Good
ADHESION TO SUBSTRATES					
Metals	Very Good	Good	Excellent	Excellent	Excellent
Plastics	Good	Very Good	Excellent	Fair	Excellent
Glass	Good	Good	Good	Excellent	Poor
Rubber	Poor	Good	Poor	Poor	Excellent
Wood	Very Good	Fair	Good	Good	Excellent
Overlapping Shear Strength	Medium	Medium	High	High	High
Peel Strength	Medium	Medium	Medium	High	Medium
Tensile Strength	Medium	Medium	High	High	High
Elongation/Flexibility	High	High	Medium	Medium	Low
Hardness	Soft	Soft	Semirigid	Semirigid	Rigid

TABLE 21

Summary of general representative characteristics of specific adhesive chemistries

PERFORMANCE CONSIDERATIONS	ADHESIVE CATEGORY				
	Cyanoacrylates	Epoxies	Hotmelts	Light Cure	Silicones
Benefits	Wide range of bonding applications, ease of use	Wide range of formulations	Versatile, fast, large gap filling	Rapid cure, adhesion to plastics, bond on demand	Excellent temperature resistance
Limitations	Low polar solvent resistance	Mixing required	Limited heat resistance	Light cure required	Low adhesion resistance
TEMPERATURE RESISTANCE					
Typical for the category	-54°C to 99°C (-65°F to 210°F)	-54°C to 87°C (-65°F to 180°F)	-54°C to 121°C (-65°F to 250°F)	-54°C to 149°C (-65°F to 300°F)	-54°C to 204°C (-65°F to 400°F)
Highest Rated Product	121°C (250°F)	204°C (400°F)	165°C (330°F)	180°C (356°F)	385°C (725°F)
ENVIRONMENTAL RESISTANCE					
Polar solvents	Poor	Very Good	Good	Good	Good
Non-polar solvents	Good	Excellent	Good	Very Good	Poor to Fair
ADHESION TO SUBSTRATES					
Metals	Very Good	Excellent	Good	Good	Good
Plastics	Excellent	Fair	Very Good	Excellent	Fair
Glass	Poor	Excellent	Good	Excellent	Very Good
Rubber	Very Good	Fair	Fair	Fair	Good
Wood	Good	Very Good	Excellent	Poor	Fair
Overlapping Shear Strength	High	High	Low	High	Low
Peel Strength	Low	Medium	Medium	Medium	Medium
Tensile Strength	High	High	Low	High	Medium
Elongation/Flexibility	Low	Low	High	Medium	High
Hardness	Rigid	Rigid	Semisoft	Semirigid	Soft

It is important to understand that application requirements dictate what bond strength is ideal and what level of strength deterioration, when exposed to different stress or environmental factors, is still adequate for bonded assemblies over the life cycle of finished goods. While a specific adhesive may exhibit a reduced strength when exposed to a particular chemical, it may still meet the strength requirements after the initial reduction in strength. Assemblies with high criticality should be manufactured, exposed to representative and controlled chemical conditions, and strength tested.

Typically, when assemblies are subjected to long-term chemical exposure, adhesive selection will generally be limited to one or two families (chemistries) of adhesives that perform well in these environments. It may be necessary to sacrifice other properties or alter process considerations to accommodate adhesives which will perform well in the respective environmental factors.

If an assembly is subjected to long-term chemical exposure, bond strength may gradually decrease to the point of failure with specific chemistries. However, some chemistries, such as epoxies or acrylates, can typically withstand long-term chemical exposure but may have process limitations, substrate limitations or temperature limitations that will need to be sacrificed or altered to meet the chemical exposure requirements.

The TDS will commonly list many of the most common chemicals that an adhesive may be exposed to, such as water, ethylene glycol, motor oil and gasoline. If data for a particular chemical is not listed, an adhesives engineer should be consulted for chemical/adhesive specific data and/or testing.

5.2.4 SUBSTRATE SPECIFICATION

The type and nature of the substrates to be bonded and the surface preparation that they may require are key factors in determining which adhesive to use. Some substrates, such as aluminium or wood, may be successfully bonded with a wide variety of adhesive types; other substrates, such as nylon or HDPE, may only be successfully bonded with a few and may require extra pre-treatment or surface preparation. In any case, not all substrates are the same, even within a substrate type, and specific attention should be given to the specification and manufacturer of a particular material, as mentioned in previous sections.

For example, 304 stainless steel is typically made by adding chromium and nickel. While the exact percentages added by weight at different manufacturers will differ, they will still be classified as 304 Stainless Steel. Adding to the complexity are other grades within the same 'family' of stainless steel (i.e. 316, 310). It is important to remember that while a substrate may belong to a 'family', they are similar but not identical.

Influences that are specific to the substrate type, such as condition, porosity, finish, acidity and alkalinity, will influence the adhesive's performance and must therefore be considered during the adhesive selection process. The surface condition of the material, its processing history and the condition at the time of bonding may be more important than the bulk substrate material properties.(17) This consideration is extremely important and often overlooked, and many issues have arisen from engineers assuming a material from one manufacturer the same as that from another manufacturer. In reality, the processes, storage conditions and surface conditions, among many other factors, may vary greatly between manufacturers.

Once a substrate has been specified in an application, great care should be taken if a change is required during production. The 'new' substrate should be validated in the process before the change is made to avoid any quality issues. If multiple suppliers of a material are to be used, each substrate should be validated independently to ensure process compatibility.

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17) Edward M. Petrie, *Handbook of Adhesives and Sealants,* McGraw-Hill, 2007.

5.2.5 CUSTOMER-SPECIFIC REQUIREMENTS AND TESTING

Since a true 'general-purpose' adhesive has not yet been developed, the end user must allow time and resources to test candidate adhesives, bonding processes, environmental resistance and finished assembly strengths. Testing and validation are extremely important steps in the adhesive process as one cannot reliably predict the strength of the adhesive bond based solely on information on the TDS as relates to characteristics of the adhesive, substrate and the joint design. To have confidence in the strength of the assembly or joint, tests should be performed. Through testing, the many factors that can affect the strength of the joint can be applied to the assembly or joint, measured and quantified, and subsequently corrected if shortcomings are identified. Sometimes it is impossible or impractical to separate the variables that affect joint strength, but through testing, a quantitative approximation can be achieved.

Standard tests, such as ASTM or ISO tests, are effective for comparing and determining the consistency of materials and processes, as has been covered in Section 4; however, they are less valuable in accurately predicting the strength of specific production joints or assemblies. Ideally, prototype assemblies should be designed and tested for this purpose. The most reliable test is to measure the strength of an actual assembly under actual operating conditions; these tests are often prohibitively expensive or impractical. The next best method is to measure the strength of an actual assembly under simulated operating conditions that do not stress the joint significantly differently from what would normally be stressed in service.(18)

The challenge herein is determining which test method one selects. It may be surprising to learn that many engineers develop testing parameters and procedures that they feel most accurately duplicate real-world conditions, rather than standardised testing methods (ASTM, ISO, DIN, etc). These tests may be complex rigs designed for repeated force application or they may be as simple as a drop-from-height test, hammer blow test or crush test. Whatever the method of testing or pass/fail criteria, it is important to have these clearly defined before engaging in adhesive selection, as this will make the adhesive selection process much simpler and lead to a higher probability of success.

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18) Edward M. Petrie, *Handbook of Adhesives and Sealants*, McGraw-Hill, 2007.

5.3 UNDERSTANDING ADHESIVE VOLUMES

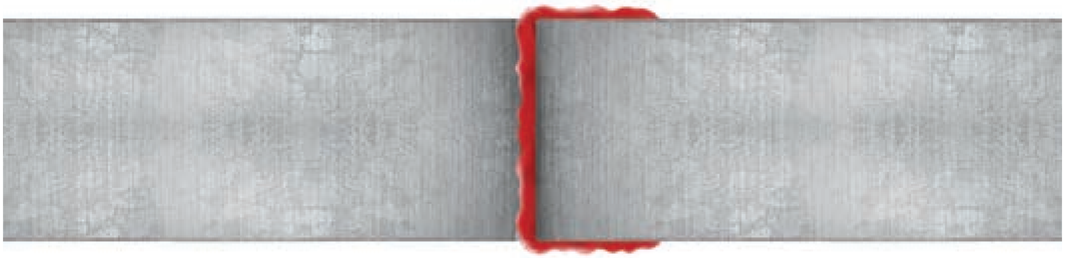
Understanding the volume of adhesive required for an application is an important aspect of the cost analysis when determining the overall cost/value of an application or assembly. Fortunately, the volume of adhesive, and subsequently the cost, can be easily calculated.

5.3.1 CALCULATING THE PHYSICAL VOLUME OF CURED ADHESIVE

The first step in any volume calculation is to consider the length, width and gap or height of the bond geometry; this will provide the basis for calculating the internal volume of the bond line. In addition to the internal volume, a factor of squeeze-out must be considered to ensure the adhesive has properly wetted the entirety of the bond line but is minimised to prevent waste. A factor of 10-20% of the internal volume should be added to account for squeeze-out. To minimise the volume of adhesive required, automated dispensing methods may be considered. For manual applications, a larger factor of wastage should be considered.

FIGURE 139

Bond line squeeze-out



5.3.2 CALCULATING ADHESIVE BEAD SIZE

Once the bond line dimensions have been calculated and the overall volume of adhesive has been determined, the next step involves factoring in the squeeze-out and calculating the appropriate bead size for dispensing. At this point, a predefined length of bond geometry based on the part design will have been established. Using the volume, bond length and radially defined bead geometry, calculating the required bead diameter is quite straightforward.

For example, here are calculations for bonding the shell of a dry freight shipping container:

20 METAL COMPONENTS	PRODUCTION
▸ 2.54 cm (1.00 in) wide ▸ 163.50 cm (64.37 in) long ▸ 0.10 cm (0.04 in) gap	▸ 4,000 containers/year ▸ 13-14 containers/day ▸ 1C adhesive cost: $20 per 300 ml cartridge ▸ Manual application: Squeeze-out factor 20%

Recommend the (1) bead diameter needed to properly fill the gap and utilise all of the available surface area. Then, calculate adhesive usage (2) per container, (3) per year, (4) per day and (5) cost.

① **Find the volume of adhesive per beam assembly.**

VOLUME = L x W x BONDLINE GAP

$$163.50\ \text{cm} * 2.54\ \text{cm} * 0.10\ \text{cm} = 41.53\ \text{cm}^3$$

② **Add squeeze-out factor of 20%**

$$41.53\ \text{cm}^3 * (1.00 + 0.20) = 49.83\ \text{cm}^3 = 49.83\ \text{ml}$$

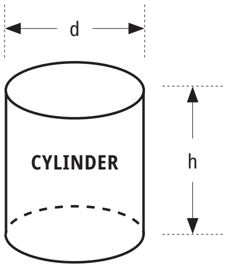
Now that we have a calculated volume per assembly, we can calculate the suggested bead diameter.

Volume of a cylinder (adhesive bead, as dispensed)

FIGURE 140

Volume of a cylinder

$$V = \frac{\pi d^2 h}{4}$$



$$V = \frac{\pi d^2 h}{4}$$

$$4V = \pi d^2 h$$

$$\sqrt{\frac{4V}{h\pi}} = d$$

$$\sqrt{\frac{4 * 49.83\ \text{cm}^3}{163.5\ \text{cm} * \pi}} = 0.62\text{cm}$$

❶ **d = 0.63cm = total bead size**

As this is an estimate, we can round our bead diameter to a commonly relatable diameter in industry 0.635 cm (¼ in) to err on the side of caution (especially if manual dispensing is involved).

The above calculation will provide you with the diameter of the aperture required for dispensing based on the volume of adhesive required to fill the calculated bond line. For specific on-part measurements, a different calculation must be used as the adhesive will not retain a perfectly cylindrical shape once dispensed.

Let's recall the original calculation of 49.83 ml per beam. As 20 beams are needed for one dry freight shipping container:

(2) Volume adhesive * total components = total adhesive container
49.83 ml/beam * 20 beams/container = 996.6 ml/container

$$\frac{996.6 \text{ ml per Container}}{300 \text{ ml Cartridge}} = 3.32 \text{ cartridges/containers}$$

There are 4,000 containers produced per year.

(3) Total Containers * Adhesive per container = total adhesive/year
4,000 * 996.6 ml = 3,986,400 ml/year

There are 13-14 containers produced per day.

(4) 996.6 ml/container * 13.5 containers/day = average 13,454 ml or 45 pieces, 300 ml tubes/day

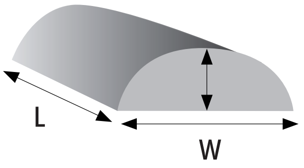
Adhesive cost is $20 per 300 ml cartridge.

(5) 3,986,400 ml/year * ($20/300 ml) = $265,760 per year

45 pieces 300 ml tubes/day * ($20/300 ml) = average $900 per day

3.3 cartridges/container * $20/cartridge = $66 per container

For an on-part calculation of the volume dispensed, see the following equation:



$$V = L\left(\frac{\pi W^2}{8}\right)$$

FIGURE 141

Volume calculation for adhesive bead

This calculation is particularly valuable when performing spot checks on adhesive volume dispensed to ensure a high degree of consistency and quality.

5.4 APPLICATION AND BOND PROCESS

5.4.1 DOSIFICATION AND BONDING PROCESS

A wide variety of dosification methods may need to be factored into the choice of adhesive for a particular assembly. Additionally, the dispensing method may affect the design of the assembly, as some methods for dispensing may not be practical for some assemblies. The final consideration is the quality or aesthetics of the final product.

The following factors should be considered when selecting the adhesive and the dispensing method:

- Size and geometry of the parts to be bonded
- Orientation of the surfaces to be bonded (horizontal/vertical)
- Areas to which the adhesive is to be applied
- Number of assemblies to be produced
- Required production speed
- Cure time of the adhesive as it relates to the total area to be bonded
- Viscosity or rheology of the adhesive
- Form of the adhesive (liquid, paste, hotmelt, etc.)
- Chemical compatibility with wetted components

The dosification method – manual/automatic dispensing or a combination of the two – is usually decided upon based on overall cost (cost-saving, additional investment, etc.), size of production, accuracy of dispensing and the importance of consistently repeatable assemblies. Whenever practical, automated dispensing lines should be incorporated into the adhesive process to maximise efficiency and accuracy and to minimise costs.

5.4.2 EQUIPMENT SELECTION

The selection of an appropriate adhesive may depend on what type of dispensing equipment is selected. Many adhesives lend themselves well to automated or semi-automated dispensing; however, the circumstances in many manufacturing situations may not justify the cost or process changes.

The following three sections describe the three basic dispensing processes and how they may impact the choice of adhesive or assembly design.

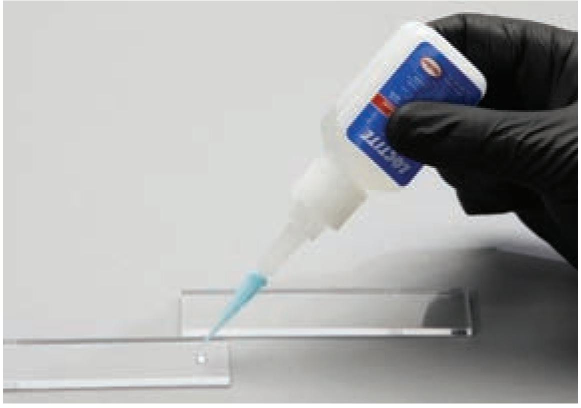
5.4.2.1 MANUAL DISPENSING

Manual dosification is currently the most common method for dispensing adhesives. This method relies on the operator to control the total volume of adhesive dispensed, the flow rate, the bead profile and bead location. This method generally involves some form of manual dispense gun, such as a cartridge gun. Many adhesives may be dispensed directly from the manufacturer's package, with or without additional consumables, such as dispense tips.

This method is usually selected when assembly or manufacturing throughput is low and quality/ consistency concerns are not significant. Manual dispensing is the highest cost method of the three, as labour costs are higher, part scrap rates are higher and adhesive tends to be overapplied, making it likely that total adhesive cost will be higher. This is particularly important when a high-cost adhesive is used and less of a concern when low-cost adhesives are used.

FIGURE 142

Manual dispensing: In this case, the adhesive is dispensed directly from the manufacturer’s package with the assistance of a dispense tip to control the application bead size and accuracy



The final consideration in manual dispensing is the human factor (covered in detail in Section 4). As the human factor relates to adhesive selection, one must account for the size of the application, the viscosity of the adhesive and the number of parts to be assembled. For example, a high viscosity adhesive dispensed in an application with a large surface area may lead to work fatigue. If incorporating dispense equipment is not feasible, a lower viscosity adhesive may need to be selected to accommodate applicator comfort.

5.4.2.2 SEMI-AUTOMATIC DISPENSING

Semi-automatic dispensing is an adhesive dosification method that incorporates the added benefit of dispense technology but also contains a human component. The volume, flow or bead size may be controlled automatically by the equipment, with the human factor controlling the placement of the adhesive on the part.

Continuing with the previous manual dispensing example, if a lower viscosity adhesive cannot be selected for the application (perhaps due to a vertical or overhead orientation), a pneumatic-powered dispense gun may be employed to prevent operator fatigue.

FIGURE 143

Semi-automated dispensing

While semi-automatic systems do not fully control for all the factors that may impact assembly quality, they do help to control for repeatability, consistency, accuracy and adhesive cost by controlling the amount dispensed.

As a general rule, semi-automated dispense processes improve quality assembly and reduce costs and operator turnover.

5.4.2.3 ROBOTIC DISPENSING

Fully automated dispensing is the ideal situation for any high-volume bonding application. With this application, nearly every aspect of the dispensing of adhesive is controlled by an automated process, which may include multi-axis robots. Adhesive volume, mixing, flow, bead size and bead location are all pre-programmed and thus have the highest accuracy and repeatability.

Nearly any adhesive can be integrated into a fully automated dispense system; however, the volume of parts produced must justify the cost of installing a fully automated line. While the overall cost per part will decrease, along with the total volume of adhesive used, there is a large upfront capital expenditure that must be accounted for.

With automated dispensing, part quality is the highest and cost is the lowest.

FIGURE 144

Fully automated dispensing, precision repeatability

5.4.3

FLUID CHARACTERISTICS OF ADHESIVES

Several additional characteristics should be considered when specifying an adhesive for an application. As with any unique fluid or paste, there will be several properties unique to the particular chemistry that will affect how and where it can be used.

Regardless of the chemistry, all adhesives exhibit one or more of these properties:

- Thixotropy
- Viscosity ranging from 'water thin' to paste (i.e. 1 mPa.s to greater than 200,000 mPa.s)
- Adhesive texture, i.e. 'stringy'
- Viscosity/temperature relationship sensitivity
- For 2C adhesives: Viscosity changes over time after mixing

5.4.4 TECHNOLOGY-SPECIFIC CHARACTERISTICS

Each technology, chemistry or product may differ regarding some of the other characteristics that need to be considered while conducting a selection process. Each technology will be covered in depth in Section 6, but many of the general adhesive characteristics are listed below.

Moisture sensitivity: Some adhesives are sensitive to moisture and may need to be stored under special conditions or used within a certain time frame once removed from the protective packaging.

Temperature sensitivity: Particularly with 1C epoxies (heat curing technology), adhesives may need to be frozen to maintain performance and prevent curing. Other technologies may need to be refrigerated to extend shelf life and performance.

Temperature-sensitive viscosity: Many adhesives will become difficult to dispense at lower temperatures due to increased viscosity. Likewise at higher temperatures, the viscosity may decrease enough to cause issues with dispensing and bead placement.

Cure time: Cure time will be affected if the adhesive is a 1C or 2C product. As a general rule, 2C adhesives have shorter cure times than 1C adhesives (with exceptions).

One-component (1C): These adhesives usually do not require special dispensing equipment and are easy to use but generally have longer cure times. They will also usually have more specific storage requirements, as they are likely to be moisture cure or heat cure.

Two-component (2C): These adhesives contain separated components and, as a general rule, are more stable to varied environmental conditions. Curing will only begin when the two components are mixed together, which may be accomplished using a static mix nozzle or an activator.

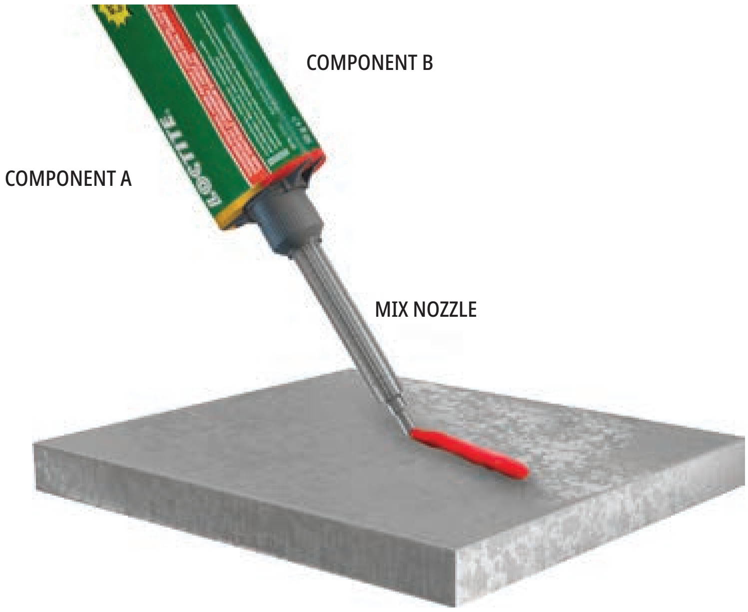


FIGURE 145

2C adhesive, mixed and dispensed through a static mix nozzle

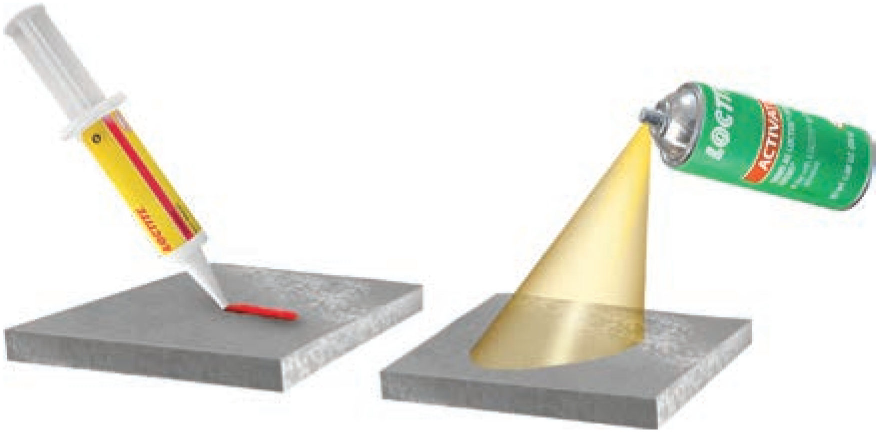


FIGURE 146

Two-step, no-mix adhesive

Mixing ratio: With 2C adhesives, attention to the specific mix ratio is required to ensure desired cured adhesive performance and results. As a general rule, high-performance adhesives will come pre-metered in dual cartridges designed to dispense the correct ratio. With larger dispensing equipment designed to metre the adhesive at specific ratios, extra attention is required.

Pot life: For 2C adhesives, there is a finite application window called pot life (covered in detail in Section 2).

UV light sensitivity: Some adhesives will react with UV light by design. These adhesives must be stored and dispensed in 'UV safe' environments to prevent premature curing.

Consumables: For 2C adhesives, the use of static mix nozzles (covered in Section 6) and extra planning, however minimal, will be required to ensure consumables are on hand.

Each characteristic should be evaluated to determine if it will fit into a production plan or if certain aspects will preclude an adhesive from consideration due to process challenges relating to the specific technology characteristic.

SECTION SIX

ADHESIVE TECHNOLOGIES

AS MENTIONED PREVIOUSLY, JOINING MATERIALS WITH ADHESIVES OFFERS SIGNIFICANT BENEFITS OVER TRADITIONAL METHODS. Despite the benefits of adhesive joining, choosing the right adhesive for a particular application can still be challenging due to the vast variety of adhesives available in the market. This section provides a summary of the different chemistries, adhesive families, physical and chemical properties, advantages, considerations and common applications, as well as the most important elements for ideal adhesive selection as they relate to the respective chemistry. If in doubt about any application, an adhesive expert should be consulted.

6.1 DEFINITION OF AN ADHESIVE

It is important to first clarify and understand the following key terminology and concepts. Doing so will help in understanding different adhesive types and their properties.

Adhesive: An adhesive is any substance that, when applied to the surfaces of the materials (substrate), bonds the surfaces together and resists separation. Adjectives may be used in conjunction with the word 'adhesive' to describe properties based on the substance's physical or chemical form, i.e. 'flexible' adhesive or 'hybrid' adhesive.

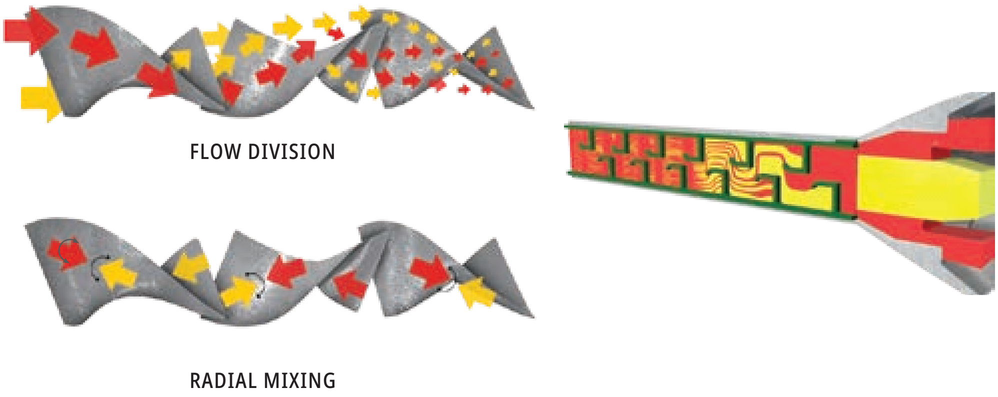
According to DIN EN 923, an adhesive is defined as a non-metallic binder that acts via adhesion and cohesion. ASTM D907-06 defines an adhesive as 'a substance capable of holding materials together by surface attachment'.

6.1.1 ADHESIVE TERMINOLOGY

Open time: The maximum allowable time between when the adhesive has been mixed (2Cs), activated or applied (hotmelt) and when the parts can be assembled without compromising the ultimate strength.

Nozzle life or dispense time: The maximum allowable time between the subsequent dispenses of 2C adhesive from the same nozzle or static mixer without causing clogging due to cured or partially-cured adhesive being present.

Static mixer: A precision-engineered dispensing device without internal moving components used for the continuous mixing of 2C adhesives. As the streams move through a static mixer, the series of baffles continuously blend the materials, as can be seen in Figures 147 and 148.


FLOW DIVISION

RADIAL MIXING

FIGURE 147

Two components (red and yellow) mixed through a static mixer

Static mixers, or 'static mix nozzles', are engineered devices that are designed to mix the 2C adhesives correctly; as such, they should not be altered in any way without first validating the performance of the mixed and cured adhesive.

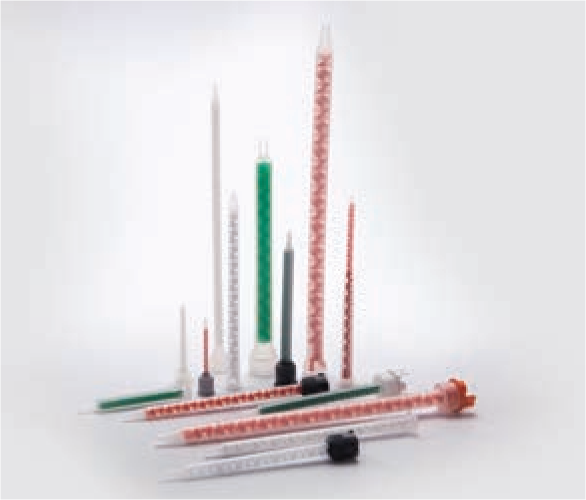


FIGURE 148

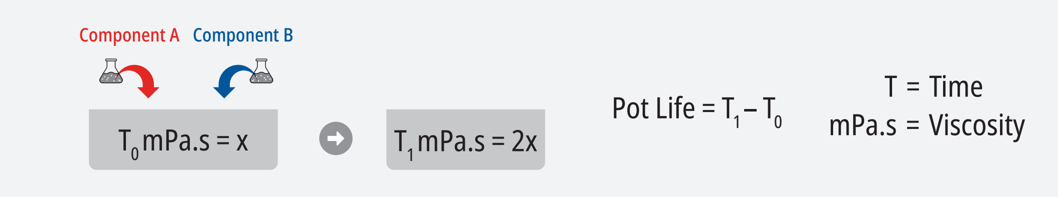
Examples of common static mixer nozzles

Working Time: The maximum allowable time between applying the adhesive to a surface and mating the surfaces without compromising the ultimate bond strength.

On-part life: Like working time, on-part life is the time before a solvent or water-borne adhesive is applied to a substrate and will no longer wet out on the surface once the mating substrate is applied. For surface treatments or activators it also defines the time over which a material will remain active on a surface or component and be usable without the need for reapplication.

FIGURE 149

Pot life of an adhesive – time for viscosity to double



Pot life: The time it takes for the viscosity of a mixed 2C adhesive system to double. For example, if we have a mixed resin system with an initial viscosity of 10,000 mPa.s and the viscosity increases to 20,000 mPa.s in 30 minutes, then the pot life of the resin system is 30 minutes. Pot life only indicates how fast or slow the adhesive system cures; it does not necessarily define the amount of time the operator has to work with the adhesive in their application.

Skin over time: Skin over time is the time it takes for the surface of the adhesive to form a skin after exposure to atmospheric pressure at 25 ± 2°C, 50 ± 5% RH.

Fixture time: The time at which an adhesive bond develops handling strength (see the definition below). The standard test method for determining the fixture time is as follows:

1. Lap shear standard 25.4 mm x 101.6 mm (1 in x 4 in) substrate joint is assembled using adhesive, overlap of 12.7 mm (0.5 in) with no induced gap
2. 3 kg (6.61 lb) mass applied to assembly
3. Time is measured to the point where a 0.1 N/mm^2 (14.5 psi) is held for 10 seconds

Full cure time: The time required for the adhesive to achieve the final desired properties. Full cure time may change with the cure temperature.

Handling strength: A (relatively) low level of overall bond strength that allows substrates to be handled, moved or unclamped without disrupting the curing process or affecting the ultimate bond strength. Note that handling strength is assembly-specific.

6.2 INSTANT BONDING

6.2.1 CYANOACRYLATES

Cyanoacrylate (CA) adhesives were first created in 1958 by Eastman Kodak, but were not fully commercialised until the 1970s. The delay in commercialisation was due to the difficulty in manufacturing and packaging such reactive materials in a way that ensured that the product remained liquid. Eastman Kodak licenced the technology to LOCTITE® in the 1970s, and with some development work on stability to improve upon the technology, a product with commercially viable shelf life was released.

The cure reaction associated with these adhesives is so rapid that they are referred to as 'instant adhesives' or 'superglue'. When pressed into a thin bond line between two surfaces, CAs cure rapidly to form rigid thermoplastics with excellent adhesion to most substrates.

CURE MECHANISM

CA adhesives are 1C, solvent-free, rapid-room-temperature-curing adhesives that are available in viscosities ranging from water-thin liquids to thixotropic gels. Their curing mechanism is activated by moisture on any surface. Figure 150 illustrates the curing mechanism of CA adhesives. In the first step, when the adhesive is applied to one surface of the substrate, the stabiliser in the adhesive keeps the adhesive from curing for a certain period. When another surface or substrate is brought into contact with the first substrate and the two are pressed together, only a thin film of adhesive remains between the two surfaces. When the joint is closed, the moisture neutralises the stabiliser in the CA, causing rapid cure to a thermoplastic material. The cure speed depends primarily on the bond line thickness and the relative humidity. Other factors are specifically related to substrate characteristics.

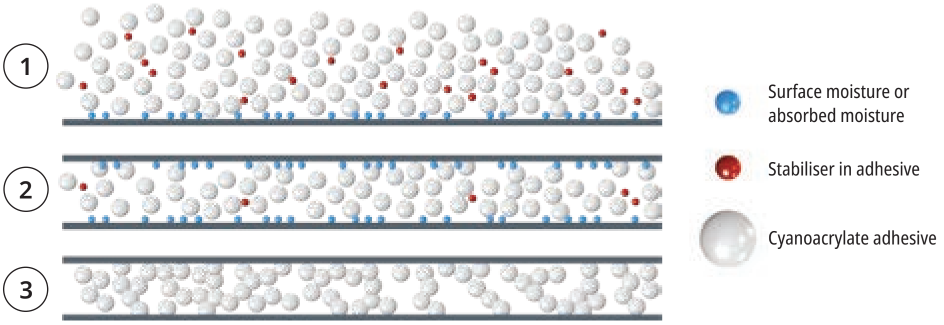


FIGURE 150

Curing mechanism of CAs

- **Step 1:** The adhesive is applied and exposed to moisture on the substrate.
- **Step 2:** The two substrates are pressed together, and the moisture on the surface neutralises the stabiliser, which leads to initial curing.
- **Step 3:** A solid polymer is formed between the two substrates, with cohesive and adhesive bonding.

GENERAL CHARACTERISTICS

Table 22 summarises the main advantages and considerations of CAs.

TABLE 22

Advantages and Considerations of CA Technology

ADVANTAGES	CONSIDERATIONS
1C system	Poor impact and peel strength
Solvent-free	Limited gap cure
Rapid room temperature cure	Poor durability on glass
Excellent adhesion to many substrates	Poor solvent resistance
Easy to dispense in automated systems	Low temperature resistance
Wide range of viscosities available	May cause stress cracking in some plastics
Excellent bond strength in shear and tensile mode	Bonds skin rapidly
Primers available for difficult-to-bond plastic	Susceptible to impact forces

Recent developments have addressed some of the considerations of CAs. For example, rubber-toughened CAs offer high peel strength and impact resistance to complement the high shear and tensile strength characteristics of CAs. Thermally resistant CAs, offer excellent bond strength retention after exposure to temperatures as high as 120°C (250°F) for thousands of hours. Moreover, 'surface-insensitive' CAs offer rapid fixture times and cure speeds on acidic or porous surfaces, such as wood or di-chromated metals, which could slow the cure of a CA. Other developments in CAs in recent years include flexible grades, 2C products for gap fill up to 5 mm and UV curing CAs.

EQUIPMENT CONSIDERATIONS

For many applications, it is sufficient to dispense the product manually directly from the bottles designed specifically for this; in other cases, however, more precise hand-held or stationary automated dispensing is required. Digital peristaltic dispense systems are a reliable, easy-to-use and cost-effective volumetric dispensing option allowing air-free dispensing directly from the product bottle.

APPLICATIONS

CAs are suitable for plastic bonding applications involving industrial plastics such as ABS, PVC, PBT, PC and PMMA. Some CAs may cause 'blooming' as shown in Figure 151. Transparent plastics and plastics with cosmetic aspects can also be bonded using low odour-low bloom technology. Flexible materials such as rubbers and elastomers can be bonded too. As mentioned in Section 4, hard-to-bond plastics such as polyolefins usually require a primer to activate the surface.

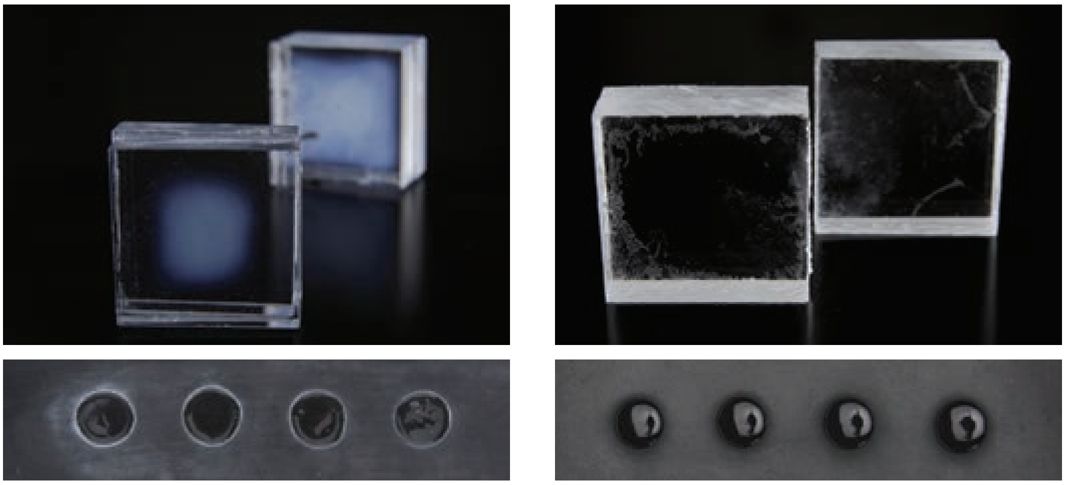
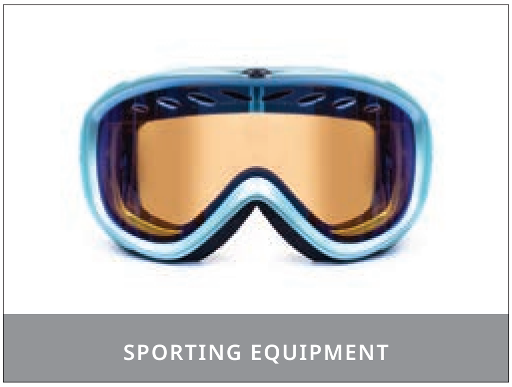


FIGURE 151

Blooming on rubber and polycarbonate (white haze) vs. no blooming on rubber and polycarbonate

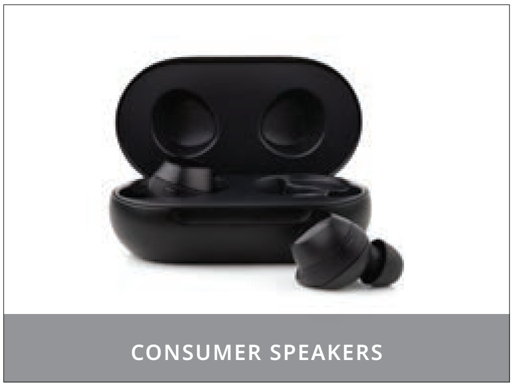
Product selection can be carried out based on the types of materials being bonded and the load to be exerted on the joint. Product selection can be further refined based on whether the joint will encounter high temperatures or be subject to peel forces. This wide substrate versatility of CAs and its ease of use has led to their application in a wide range of general manufacturing and maintenance environments.



Hekla/Shutterstock

FIGURE 152

CA adhesives are commonly used in sporting equipment and rubber bonding applications



Sergey Eremin/Shutterstock

FIGURE 153

CAs are also used in a wide variety of consumer goods, ranging from cosmetics cases and plastic enclosures to consumer electronics, including speakers

6.2.2 TWO-STEP, NO-MIX ACRYLICS

Two-step or no-mix acrylic adhesives consist of a resin and an activator. The resin component is a solvent-free, high-viscosity liquid, while the activator is a low-viscosity liquid catalyst. Typically, the activator is applied to one of the substrates to be bonded while the resin is applied to the other. Upon mating the two substrates, the activator meets the adhesive and catalyses the breakdown of peroxide in the adhesive to form free radicals. These free radicals then cause the adhesive to polymerise to a thermoset plastic. The key here is that the resin and activator do not start reacting until the two substrates are mated, highlighting the key attribute of this adhesive system: practically unlimited open time.

Considerations for 'activator'-only selection

There are different types of activators available for use with 2C and two-step no-mix acrylic adhesive systems. Generally, activator selection is based on four criteria:

- **Fixture time (for two-step no-mix acrylics)** – a measure of how quickly the adhesive cures.
- **Bond strength** – the ultimate strength of the bond, which is heavily affected by the type of activator chosen (the activator can also affect the environmental durability of the bond).
- **On-part life of activator** – the useful life of an activator once it has been applied to a part. On-part life can range from 30 minutes to 30 days. The longer the on-part life of the activator, the easier it is to integrate its use into the manufacturing process.
- **Activator form** – one of the three forms in which activators are supplied:
    - Active ingredient dispersed in a volatile solvent
    - Active ingredient dispersed in a non-volatile solvent
    - 100% solids formulations containing no solvents.

Each form has unique processing and economic demands that must be considered to identify the optimum solution for each application.

Considerations for using volatile activators

These activators are typically applied to one surface, the solvent evaporates and the activated surface is mated with the surface which has resin dispensed on it. This rapid evaporation minimises the time required between the activator dispensing step and the parts mating step. Additionally, since the active ingredient is present at low levels, it is very difficult to apply too much of it.

The main limitation of these systems is the flammability of the carrier solvent. There are activators formulated with non-flammable carrier solvents. However, the cost of these activators can be prohibitive.

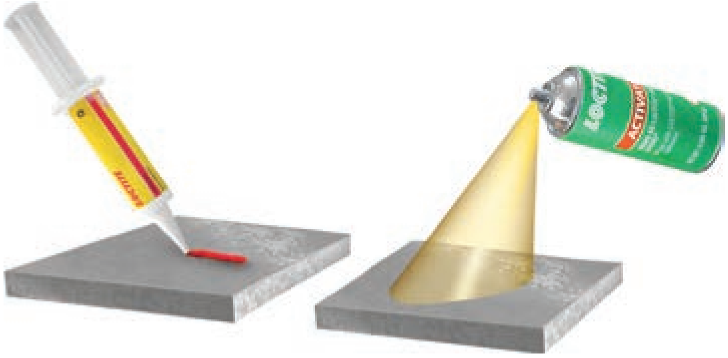
Proper precautions must be taken while using volatile activators. In some cases, explosion-proof dispensing equipment must be used. Irrespective of flammability, local regulations may consider the solvent as VOCs and limit their release to the environment. Additionally, proper ventilation is needed to ensure that the solvent level in the work environment does not present a health hazard.

CURE MECHANISM

As mentioned earlier, two-step acrylates are used by applying the resin to one part and the activator to another. The two parts are then mated to initiate cure. Figure 155 illustrates the actual curing process.

FIGURE 154

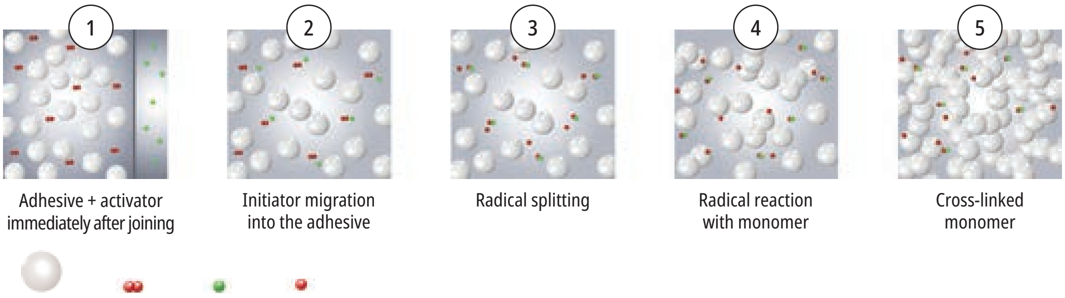
Application of adhesive and activator to separated substrates



In the first step, directly after the parts are mated together, the activator and resin are still separate from each other. However, the activator immediately starts diffusing into the resin. This is shown in the second step of the figure. In the third step, the activator reacts with the cure initiator and starts forming the radicals, which then react with monomer to form a crosslinked polymer network, as shown in the fourth and fifth steps.

FIGURE 155

Two-step, no-mix acrylics cure



Adhesive + activator immediately after joining

Initiator migration into the adhesive

Radical splitting

Radical reaction with monomer

Cross-linked monomer

GENERAL CHARACTERISTICS

Table 23 summarises the main advantages and considerations of two-step acrylics.

TABLE 23

Advantage and considerations of two-step acrylics

ADVANTAGES	CONSIDERATIONS
Fast fixture speed	Limited cure through depth 1 mm (0.04 in)
Room temperature cure	Activator may contain solvents
No mixing required	Activator requires controlled dispensing process
High peel and impact strength	Adhesive may have strong odour
Good environmental resistance	
Bonds to lightly contaminated surfaces	
Cure can be accelerated with heat	

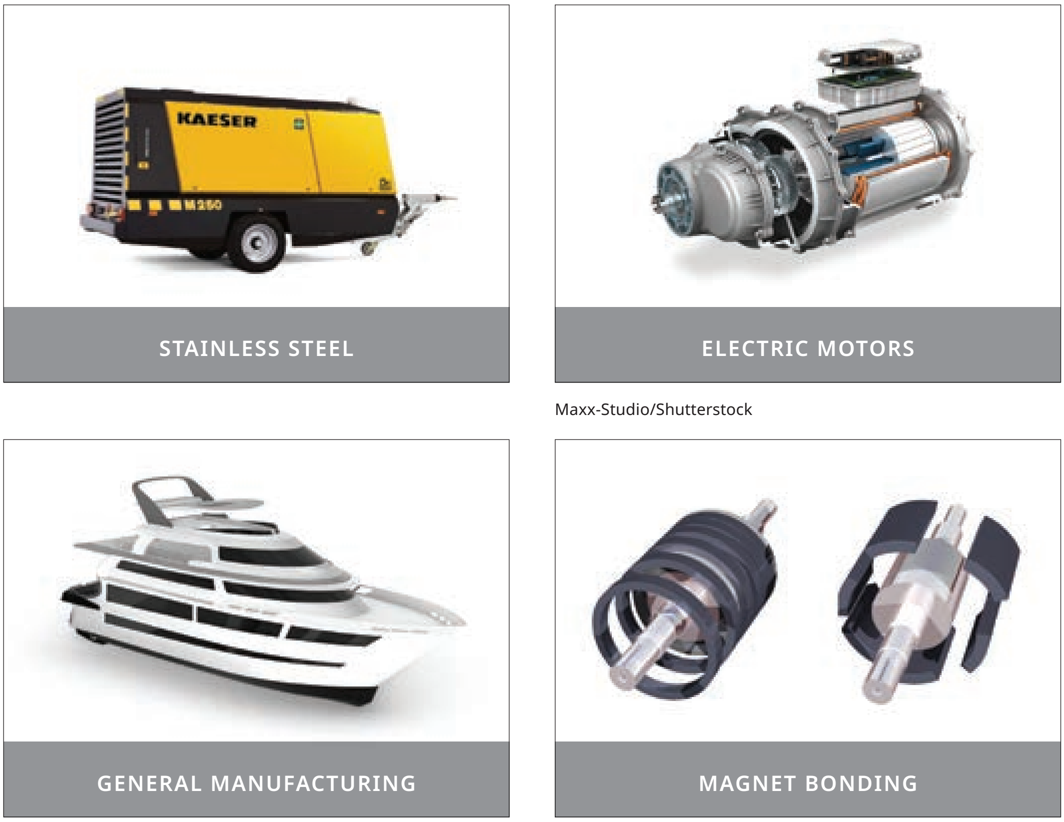
APPLICATION CONSIDERATIONS

- None of the activators are compatible with all resins. Follow the resin TDS to find the appropriate activator.
- It is important not to overapply the activator.
- While using solvent-based activator, allow time for solvent evaporation in the process.
- Do not apply activator and resin to the same part.
- When bonding porous materials, apply the adhesive to the most porous surface. Low viscosity activators may be absorbed by porous materials and drawn away from the surface and from contact with the adhesive.

EQUIPMENT CONSIDERATIONS

Equipment to dispense these kinds of adhesives will depend on the package size and could vary from a manual squeeze bottle to the most sophisticated automated equipment. Two separate dispensing systems may be needed: one for the resin and another for the activator.

APPLICATIONS



STAINLESS STEEL

ELECTRIC MOTORS

Maxx-Studio/Shutterstock

GENERAL MANUFACTURING

MAGNET BONDING

FIGURE 156

Common applications for two-step, no-mix acrylics cure

6.2.3 LIGHT CURE ADHESIVES

Light curing adhesives cure when exposed to UV radiation from a light source. There are several light cure product families, including acrylates, CAs, silicones, epoxies and anaerobics; however, the most predominant technology is light cure acrylate. For many of the product families, light curing alleviates some of their disadvantages, such as long cure times, process challenges or depth of cure challenges. For example, light cure CAs have a dual-cure mechanism using both UV/visible light as well as the traditional surface moisture cure (see Section 6.2.1 for more details). This mechanism helps to cure CAs in applications where a large cure through gap is present, with the surface moisture cure mechanism allowing for a full cure in areas not exposed to light. Additionally, light cure adhesives reduce blooming, which can be an issue with some standard grade CA products, particularly when bonding plastics.

TABLE 24

Summary of light cure technology benefits

TECHNOLOGY	KEY BENEFIT	SECONDARY BENEFIT
Light cure silicone	Fast cure	Low temperature flexibility, high moisture resistance
Light cure anaerobic	Faster cure over traditional anaerobics, higher depth of cure	Dual cure in shadowed areas, better cure on inactive substrates
Light cure epoxy	On demand curing without heat	1C product
Light cure cyanoacrylate	Instantaneous curing	No blooming, shadow cure
Light cure acrylates	Very fast cure	1C, solvent free

Light curing acrylic adhesives are supplied as 1C, solvent-free liquids with viscosities ranging from 50 mPa.s to thixotropic gels. The cure times of light curing acrylic adhesives depend on many parameters; however, cure times of 2 to 60 seconds are typical and cure depths up to a maximum of 12.7 mm (0.5 in) are possible.

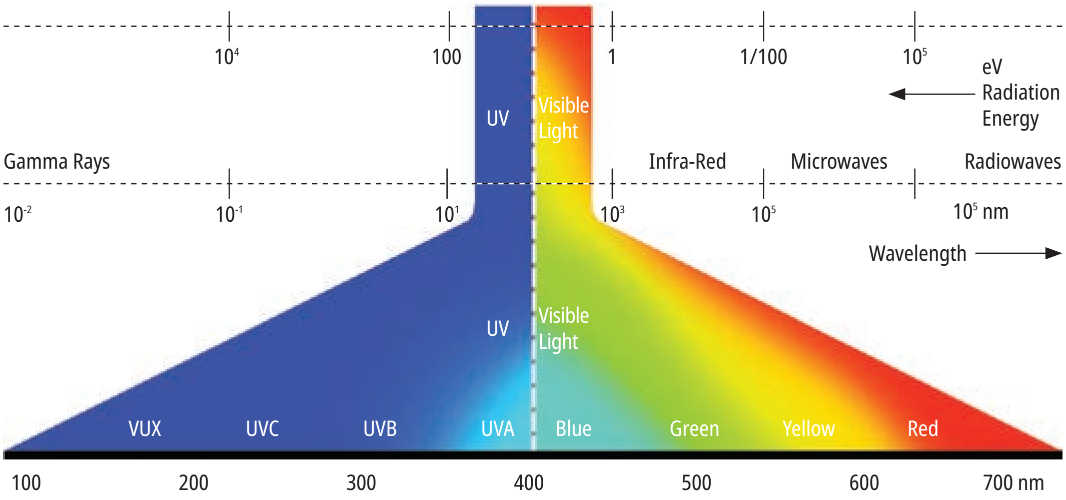


FIGURE 157

The electromagnetic spectrum

CURE MECHANISM

UV light curing technology offers manufacturers ease of use and increased productivity over traditional heat curing or 2C curing adhesives. Light cure adhesives are formulated with a special kind of cure initiator, called a photo initiator, which breaks down into free radicals when exposed to UV light of the appropriate wavelength and intensity (see Figure 158). These free radicals then react with the monomer in the adhesive. Eventually, when all monomer species have reacted, it forms a thermoset polymer.

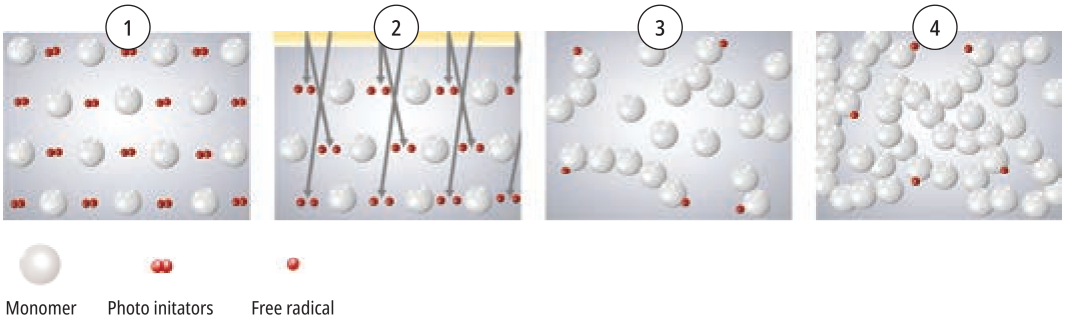


FIGURE 158

Free radical polymerisation process in UV cure products

GENERAL CHARACTERISTICS

Table 25 shows the typical advantages and considerations of a light cure acrylic.

TABLE 25

Advantages and considerations of light cure technology

ADVANTAGES	CONSIDERATIONS
Cure on demand	Light must be able to reach bond line
Good environmental resistance	Oxygen can inhibit surface cure
Wide range of viscosities available	Additional equipment is required for curing
Solvent-free	Exposure of operators to UV radiation
Gap filling	Potential for ozone with some systems
1C; no mixing required	
Dispensing can be easily automated	
Clear bond lines	
Rapid fixture and complete cure	
Wide range of physical properties	
UV/visible cure systems available	
Fluorescent dyes can be added to ease inspection/detection	

EQUIPMENT CONSIDERATIONS

Light cure adhesives are typically dispensed directly from the bottle and directly onto the substrates, but handheld or stationary automated dispensing equipment may be used for high-precision applications. Owing to their cure-on-demand property, light cure adhesives lend themselves well to automated high-speed assembly lines. Various light bulb and LED technologies ensure the proper wavelength adapted to the adhesive selected and the transparency of the parts to be bonded.

APPLICATIONS

Light cure adhesives are suitable for any application where light easily reaches a bond line (i.e. substrates are transparent or translucent). Traditional applications include glass furniture bonding, jewellery, ornaments, lighting and medical devices. Light cure acrylics also provide tremendous strength with plastic assemblies. Typical applications in this area include housings, nametags and loudspeakers. Dual cure products, such as light cure anaerobics, are often used in motor bonding for bonding magnets to metal housings or rotors. Light cure products have also found a home in the electronics industry, specifically in touchscreen displays, loudspeakers and other hand-held devices. Other applications include potting, encapsulating, lens bonding, wire tacking, edge bonding of display materials and in display lamination. Light cure epoxies are typically used in computer chip bonding.

One of the most important application groups for light cure acrylics is within the medical industry (particularly cannula and needle-bonding). Many light cure adhesives now carry medical grade certification to confirm their biocompatibility in such industries. The rapid and controllable cure mechanism of light curing adhesives allows for immediate progression down a production line. This key feature makes light cure acrylics ideally suited to high-speed production lines.

FIGURE 159

Typical applications for light cure adhesives


MEDICAL


ELECTRONIC

Maxx-Studio/Shutterstock


APPLIANCES


AUDIO VISUAL

6.3 FLEXIBLE BONDING AND SEALING

6.3.1 SILANE-MODIFIED POLYMERS

Silane-modified polymers (SMPs) or silyl-terminated polymers (STPs) possess an organic polymeric backbone (polyethers, PUs) terminated with reactive alkoxysilanes(19). These adhesives are formulated with room temperature cure catalysts. SMPs start curing when exposed to atmospheric moisture and form an elastic crosslinked polymer. When the SMP has a polymeric backbone of polyethers, the system is known as a modified silicone (MS) polymer. When the polymeric backbone is PU-based, it is known as a silyl-modified polyurethane (SPUR) polymer; both are a subclass of SMPs as they have similar chemistry and features. SMPs combine the strength of PUs/polyether with the environmental resistance of silicones(20). In addition to their high-performance properties, this product family has gained popularity due to its solvent-free and isocyanate-free nature. Because of the similarity of their polymer backbones, collectively, these polymers are generally referred to as SMPs. SMPs, upon curing, always release methanol or ethanol as a by-product; thus, they are neutral cure technology.

6.3.2 1C AND 2C SMP COMPOSITIONS

A 1C SMP adhesive cures using the moisture in the air, while 2C systems cure via an added water paste as a second component. This system makes 2C SMP adhesives cure much faster than 1C systems, independent of environmental relative humidity.

CURE MECHANISM

A 1C SMP product requires atmospheric moisture to facilitate the hydrolysis and condensation process; the curing process starts when the uncured polymer is exposed to atmospheric moisture. Initially, curing starts with skin formation on the surface and then gradually proceeds inward. The cure rate is directly dependent on the environmental relative humidity and temperature. Note that adhesive strength may continue to develop for one to two weeks after application due to the 'outside–in' curing. Faster cure speeds can be achieved through introduced moisture and increased temperature.

1C Cure

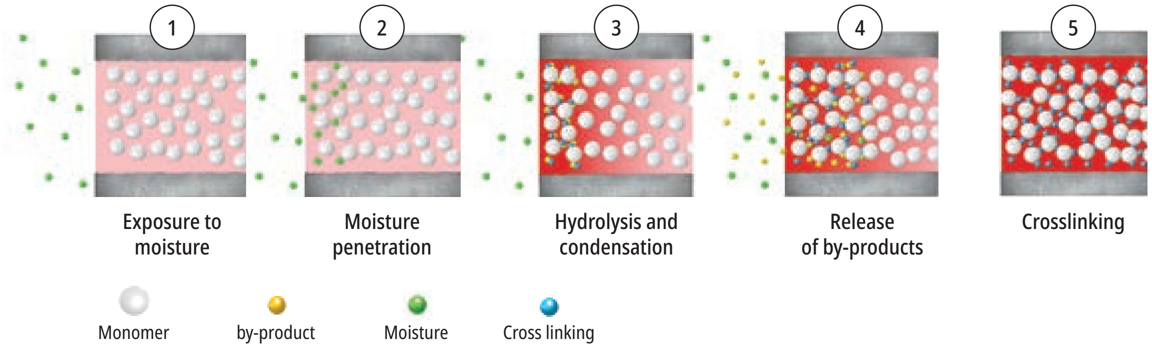


FIGURE 160

1C-SMP curing mechanism

- **Step 1:** SMP is exposed to atmospheric moisture after dispensing.
- **Step 2:** The moisture migrates into the uncured SMP from the outside to the inside.
- **Step 3:** Moisture contact will initiate hydrolysis followed by condensation.
- **Step 4:** Alcohol liberates out as a condensation by-product.
- **Step 5:** Crosslinking starts immediately after condensation.

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19) Proebster, Manfred. *Industrial sealants.* Landsberg am Lech, Germany: Verlag Moderne Industrie, 2004.

20) Austerberry, Michael. *'Silane-Modified Polymers (SMP) Combining the Best of Silicone & Organic Polymers.'* International Silicone Conference –May 17, 2016. 2016. 1-25.

A 2C SMP follows a moisture curing mechanism similar to 1C SMPs; however, unlike 1C systems, 2C systems cure independently of the atmospheric moisture. As such, 2C systems are almost always faster than 1C systems while achieving a greater depth of cure. SMPs are inherently stable, both with moisture in the absence of catalysts and with catalysts in the absence of moisture; however, when catalysed systems are exposed to moisture, they immediately start gelling through hydrolysis, followed by condensation cure.

2C Cure

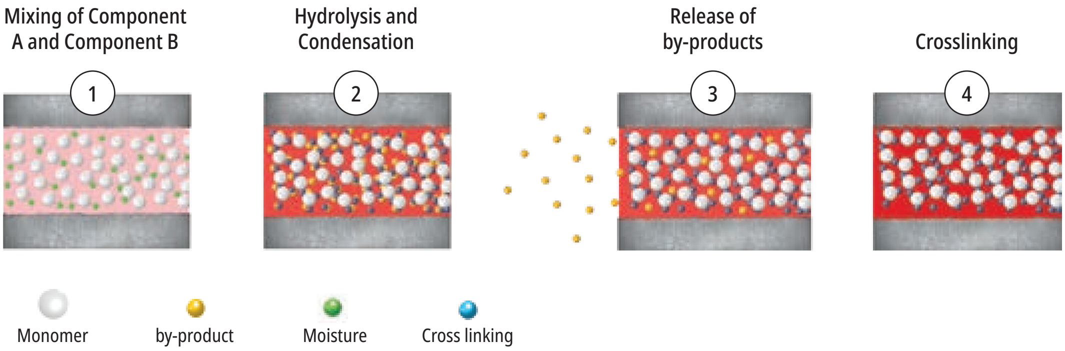


FIGURE 161

A 2C SMP curing mechanism

- **Step 1:** Components A and B are mixed before making an SMP application.
- **Step 2:** Hydrolysis and condensation start in the system.
- **Step 3:** Alcohol liberates out as a condensation by-product.
- **Step 4:** Crosslinking starts immediately after condensation.

GENERAL CHARACTERISTICS

SMPs are available in a variety of viscosities, from self-levelling or flowable to sag-resistant pastes suitable for vertical or inverted applications. Additionally, they may be formulated as tough, sprayable elastic coatings. They also offer top to bottom (outside – in) curing upon exposure to moisture. Skin formation time varies from 3 to 60 minutes depending on formulation, with a curing rate of 2-5 mm (0.08 in – 0.20 in) in 24 hours. When SMPs are formulated as elastic sealants, they offer tensile bond strengths varying from 1 to 3 N/mm^2 (145 – 435 psi) and elongation >400%. At the same time, when used as a flexible adhesive, bond strengths ranging from 2 to 10 N/mm^2 (290-1,450 psi) and elongation varying from 100-400% can be seen. SMP formulations commonly provide a hardness of around 20-70 Shore A. As strength is related to curing, 2C systems develop strength quickly compared to 1C systems and are therefore well suited to high-speed manufacturing processes.

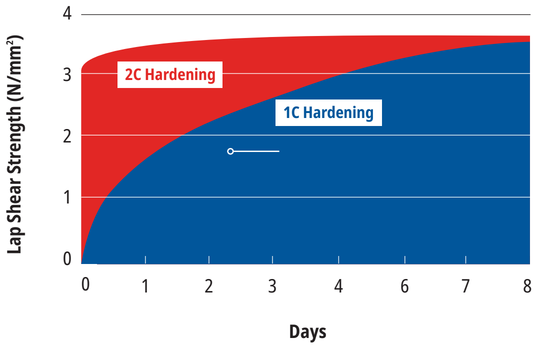
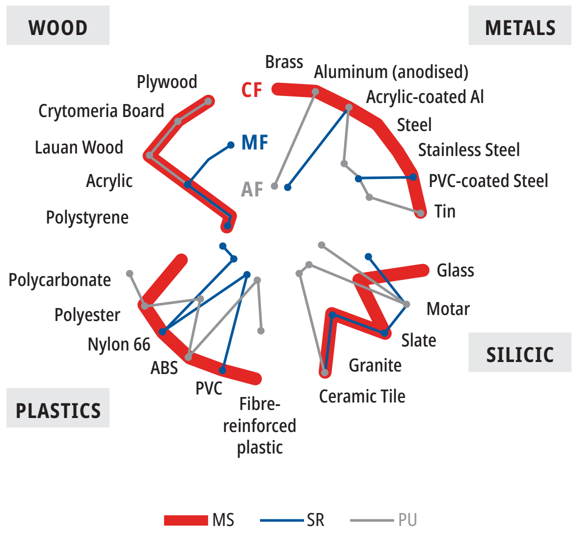


FIGURE 162

Crosslinking of 1C and 2C systems – lap shear strength measured over time

The properties of cured polymers can be engineered to range from very soft, low-modulus sealants to harder, higher-modulus adhesives with greater strength. Additionally, they have good flexibility over a wide temperature range of -50°C to 100°C (-58°F to 212°F), and clear colour and odour. SMP-based elastic bonding adhesives are particularly suitable for bonding large surface areas where high green strength is required. They offer excellent adhesion on a wide range of substrates and provide superior performance to silicones and PUs. Additionally, they offer primerless bonding to glass, ceramic frit, low-energy plastics and many other surfaces.

ADHESION ON VARIOUS SUBSTRATES



MS: SMP	PU: Polyurethane	CF: Cohesive failure
SR: Silicones	AF: Adhesion failure	MF: Mixed failure

FIGURE 163

Adhesion of SMP on various substrates

F164

F165

FIGURE 164

Primerless adhesion on plastic substrates

FIGURE 165

Elasticity and flexibility of SMP composition

TABLE 26

Advantage and considerations of SMP polymer technology

ADVANTAGES	CONSIDERATIONS
Environmental friendliness (solvent-free, isocyanate-free and halogen-free)	Hazardous raw material classifications (health and safety)
Low-temperature dispensability (viscosity is less dependent on temperature changes)	Temperature limitations 80°C (176°F)
Stain resistance sealants will not stain substrates	Formulations sensitive to moisture
SMP sealants provide good paintability (PU ≥ SMP >> Silicones)	Loss of bond strength over time when bonding glass and directly exposed to UV light. Specialty black primers are formulated to prevent this.
SMP sealants provide primerless adhesion to various substrates, including metals, plastics, wood, paints and ceramics	
SMPs are UV stable over long durations of exposure	

EQUIPMENT CONSIDERATIONS

A 1C SMP is simple to use and apply and requires no special preparation. These products can be applied with standard adhesive tubes and handheld cartridge dispense guns or fully automated dispensing systems utilising pails or drums. A 2C SMP is available in mixing ratios ranging from 1:1 to 10:1, depending on the application process and performance requirements. In general, 2C high-ratio SMPs are best mixed and dispensed by robotic systems. Low-ratio 2C SMPs are well suited for manual application.

APPLICATIONS

- Elastic bonding and sealing of recreational vehicles and motor coaches
- Elastic sidewall bonding of motor coaches, trains and goods carriers
- Adhesives and sealants for buildings and construction
- Façade, wood and panel bonding
- Glass bonding for appliances
- Mirror bonding for solar panels
- Automotive-sprayable seam sealing
- Frame bonding of photovoltaic modules
- Insulation panel bonding
- Joints for building constructions and industrial applications
- Sprayable thick film coatings
- Structural bonding which requires elasticity and high strength
- Spray or brush application in Vehicle Repair and Maintenance (VRM) seam sealants

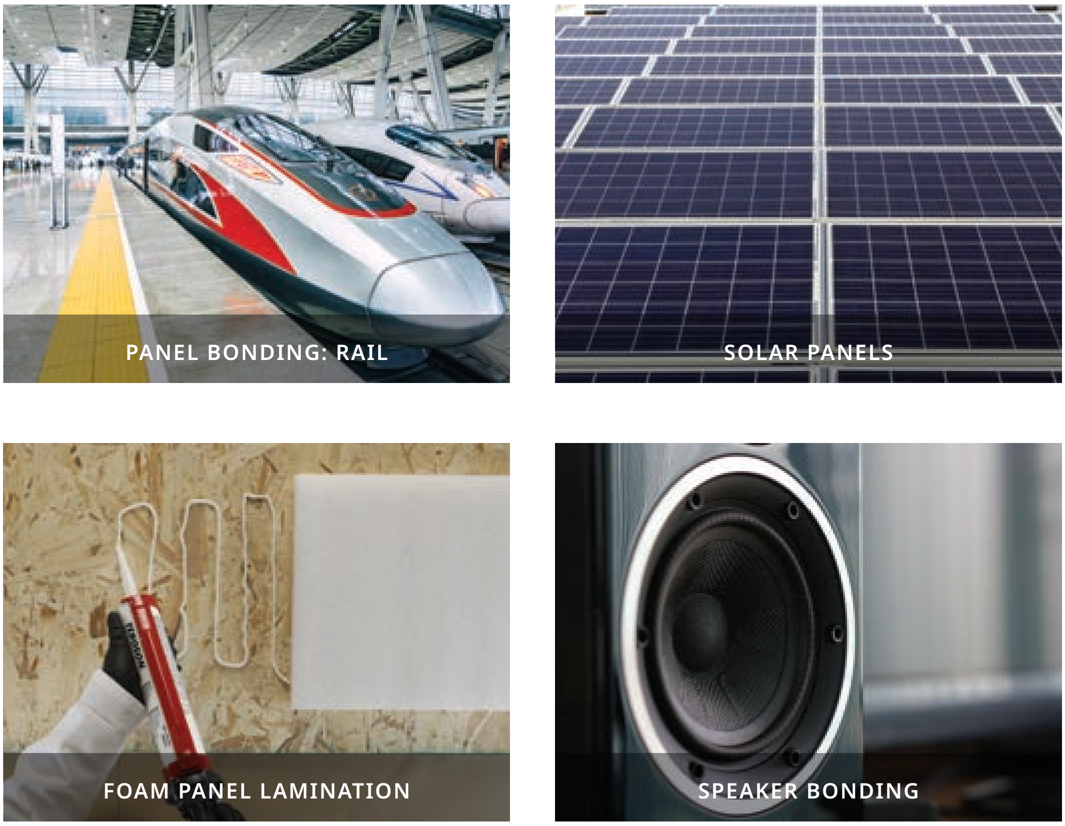


FIGURE 166

Common applications of SMP technology

Ridtee Chotechuang / Shutterstock

6.3.3 POLYURETHANE (PU)

PU adhesives derive from the presence of the chemical group urethane in the formulated or cured product.(21) PUs possess the widest range of curing rates, processing flexibility and mechanical properties due to the versatility of PU chemistry. PUs offer outstanding adhesion to substrates containing hydroxyl groups, such as wood and wood-derived materials, brickwork, concrete and certain plastics and paints. However, substrates such as glass, aluminium and alkaline substrates need primers to develop a strong bond. In addition to promoting adhesion, primers protect the adhesive from negative interactions with the substrate.

Because of their ease of use and low cost, 1C PU sealants have almost entirely replaced 2C polysulfide sealants in the construction industry. The continuous temperature resistance of PU sealants is generally 90°C (194°F), which is adequate for many industrial commercial and residential applications. Some grades can change colour to pale yellow and become brittle when exposed to UV light for a long duration; this often manifests as cracking and a 'chalky' powder on the surface. However, some grades can overcome this disadvantage. In their fully cured state, PU sealants are highly resistant to water and aqueous salt solutions, even at high temperatures, but they can be permanently damaged by strong bases and acids. Many polar organic solvents give rise to reversible swelling and, in turn, to a change in mechanical properties. Since the resistance of a sealant to media also depends on the geometry of the joint and other external factors, tests must usually be carried out to ensure the suitability of a product for a particular application.(22)

The solvent content of most PU sealants improves flow characteristics by lowering their viscosity and in many cases, improved wetting of the substrate occurs, subsequently improving adhesion. The disadvantage of a relatively high solvent content (up to 15%) in many PU sealants is pronounced shrinkage, which becomes apparent during curing. This may cause distortion in the final assemblies, and the sealant may develop internal stresses.

PU sealants lend themselves particularly well to coating with 1C or 2C varnishes and paints containing solvents. Many 1C paints are also based on PU chemistry and are therefore highly compatible with the sealant. With the wet-on-wet method, the paint can be applied directly over uncured PU sealant and both sealant and paint can cure together. However, 2C paints are highly resistant to the diffusion of moisture, which can retard the curing of the sealant. Unlike many other sealing systems, PU sealants can readily be painted when fully cured. The paintability and low cost of PU sealants are advantageous for the transport industry, vehicle manufacturers and vehicle repair shops.

If the cure speed of 1C PU sealants is inadequate, 2C products can be used. The base resin and isocyanate hardener are supplied in separate packages and must be intensively and evenly mixed before use so that a homogeneous curing sealant is obtained.

Glazing Technology (DGX)

FIGURE 167

Professional windscreen/ windscreen bonding

Today's automotive windscreens or windscreens are installed exclusively using the direct glazing method, building on the technique first used in 1960. Since then, this method has become the standard procedure for cars, buses, trucks, trains and many other vehicles.

The bonded windscreen is now a safety-critical component of vehicles; it ensures the full functionality of the safety restraint systems and airbags. In addition, the windscreen enhances the torsional rigidity of the car body by up to 40%. Furthermore, many new driver assistance systems such as distance sensors, cameras, head-up displays and rain sensors are integrated into the windscreen area of automobiles.

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21) Proebster, Manfred. *Industrial sealants.* Landsberg am Lech, Germany: Verlag Moderne Industrie, 2004, 37.

22) Proebster, Manfred. *Industrial sealants.* Landsberg am Lech, Germany: Verlag Moderne Industrie, 2004, 37-40.

CURE MECHANISM

The DGX windscreen bonding portfolio includes three types of adhesive for this application: 1C adhesives, accelerated 1C adhesives and 2C adhesives. All of these are PU-based and are constantly being developed to meet changing and growing customer requirements.

The 1C PU DGX bonding adhesives consist of isocyanate-terminated prepolymers, which cure by reacting with the surrounding humidity. After application, the adhesive bead gradually hardens from the outside inwards. The curing takes place via the reaction of the prepolymers with the water molecules diffused over the boundary phase. Thus, the curing speed strongly depends on the surrounding temperature and humidity. While high temperature and humidity lead to rapid hardening during processing, hardening is relatively slow at low temperature and humidity. In the course of this reaction, CO^2 is formed and released. The open-pored structure of the carbon black within the formulation helps absorb the CO^2 or transport it to the outside.

FIGURE 168

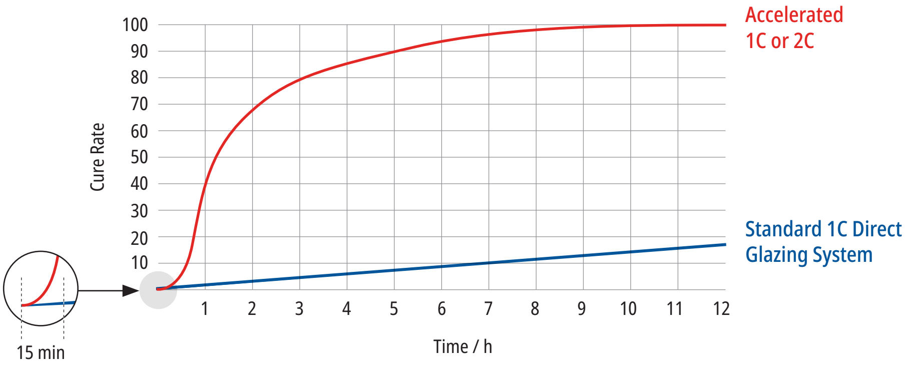
Example of an accelerated 1C DGX windscreen adhesive

The curing process of accelerated 1C DGX windscreen adhesives is the same as for 1C adhesives. The moisture containing accelerator is mixed into the adhesive during application. Therefore, a specially designed container is placed between the cartridge and nozzle. By using this method, it is possible to achieve very high strength levels after only a short time.

A 2C DGX windscreen adhesive consists of a polyol component and an isocyanate component, which are in different cartridges and are mixed during the application process via a suitable static mixer. This type of adhesive cures through a direct reaction between the two parts of the adhesive. The advantage is that, due to its largely climate-independent curing, the adhesive provides high process reliability even at low temperatures and extremely low levels of humidity. Special application tools for two cartridges, as well as a suitable static mixer, are required for the application.

FIGURE 169

Curing rate process of 1C vs 2C (DGX adhesives)



GENERAL CHARACTERISTICS

DGX windscreen adhesives are highly viscous PU adhesives that fill the gap between the windscreen and the car body and solidify to form a structural elastic bond. First, the adhesive helps to ensure the full functionality of the windscreen. Second, in a cured state, the bonding material delivers the needed transmission and/or absorption of different forces and energies acting on the car body and windscreen and enhances the structural rigidity of the car in its daily use. The advantages of 1C PU adhesives are their independence from the mixing ratio, only simple application tools are needed, they are easy to handle and they provide high process reliability. The skin-forming time of 1C PU adhesives and other specific properties are set, depending on the requirements, through the composition of their formulation. Although monomers with lower volatility are used, the proportion of nonreactive and still very reactive monomers or residual monomers remains an essential factor for the subsequent identification of the adhesive.

EQUIPMENT CONSIDERATIONS

Direct glazing windscreen installation allows automotive glass fitters or independent technicians using manual, pneumatic or battery-operated dispensing guns to replicate as closely as possible the speed and reliability of original equipment manufacturers (OEM) using bulk dispensers and robots.

TRENDS

Trends in the automotive industry have led to the installation of many new technical devices in and around the windscreen area, such as advanced driver assistance systems. Today, while there are already numerous electronics and sensors to assist drivers, many technologies are still in their early stages and there is certainly much more to come, such as autonomous driving, which will have an impact on windscreen bonding in one way or another.

YESTERDAY	TODAY	TOMORROW
No driver assistance systems available. All commands executed by the driver.	Assistance systems support the driver with traffic information, sign detection, braking systems, acceleration/deceleration, etc.	In the future, autonomous driving will be possible with no active decisions on the part of the driver.

hfng / Shutterstock

FIGURE 170

Ongoing developments in and around the windscreen area of cars

6.3.4 SILICONE

Silicones are unique materials that combine the advantages of glass (silicone-based) and plastic (carbon-based). Like glass, silicones are temperature and moisture resistant, chemically inert and have good dielectric properties. Similar to plastics, silicones can assume many shapes and forms and remain strong and flexible while exhibiting excellent thermal stability.

Broadly speaking, 1C silicone elastomers have outstanding properties and are far superior to conventional organic elastomers. They exhibit excellent mechanical strength in harsh environments and can be used at temperatures ranging from -50°C to +350°C (-58°F to +660°F). They typically possess hardness in the range of 30-80 Shore A, excellent tear strength (15-40 N/mm^2) and elongation at break varying from 150% to 800%. The ageing resistance of silicones highlights their core qualities: they are chemically inert, photo-oxidatively stable and free from residual reactive groups once cured.

Silicones are classified based on the curing method as follows:

1. 1C condensation cure RTV
2. 2C condensation cure RTV silicones
3. 2C addition cure RTV silicones
4. 1C heat cure silicone rubbers
5. UV-curing silicone rubbers

6.3.5 1C CONDENSATION CURE RTV SILICONES

CURE MECHANISM

In general, the curing process seen in silicone adhesives is known as vulcanisation, which is the change from a liquid to an elastic body. The crosslinking of silicone rubber starts when the material contacts atmospheric moisture;(23) skin formation occurs on the material's surface and then gradually cures inward through the adhesive bulk.(24) The rate of cure is reliant on and directly proportional to the relative humidity and temperature of the environment. Silicones cure from the outside in; depending on the volume of adhesive, strength may continue to develop for several weeks after the silicone is applied until fully cured.

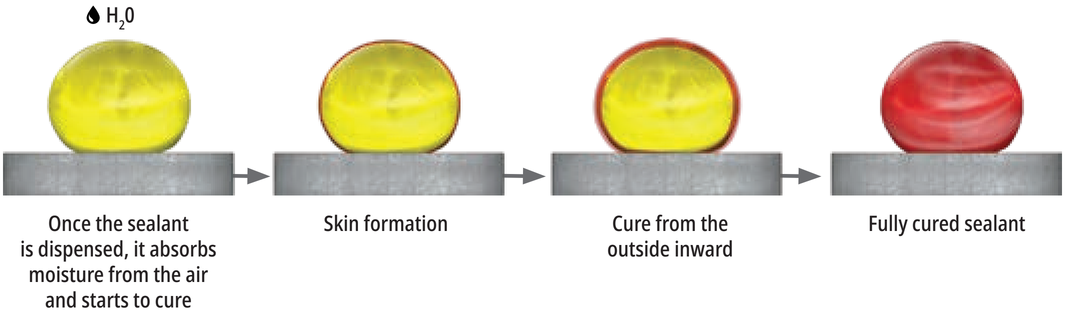


FIGURE 171

Curing phenomenon of moisture-curable silicones

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23) R, Tang Y and Tsiang, 'Rheological, extractive and thermal studies of the room temperature vulcanized polydimethylsiloxane,' *Polymer*, 1999, 6135–6146.

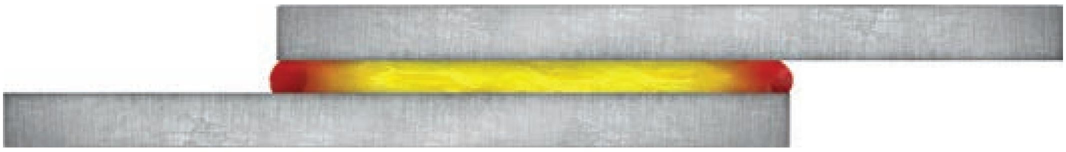
24) https://www.antala.uk/wp-content/uploads/2016/07/Dow-Corning_Selector-Guide_AntalaUK_digital.pdf.

GENERAL CHARACTERISTICS

The cure rate for these compositions is limited by the diffusion speed of moisture, which typically averages 1-3 mm (0.04 - 0.12 in) per day at 23°C (73°F), 50% relative humidity and one atmosphere of pressure. A 1C condensation cure product will not cure in depths greater than 10 mm (0.40 in) because moisture cannot penetrate past this point.

FIGURE 172

Inability of some 1C products (silicones etc.) to cure through large gaps due to the moisture dependent curing process



During the vulcanisation process, a by-product is released, which varies with the type of product. In some cases, this by-product can be corrosive, and care must be taken to ventilate the production area while using this adhesive. Additionally, silicones which out-gas corrosive by-products should not be used for enclosures that are not vented or contain sensitive components and materials (i.e. gear covers, electrical enclosures).

The 1C condensation cure silicone system is an ideal solution for numerous sealing, bonding and coating applications. This system achieves good adhesion on different substrates and can range from 15 to 60 Shore A hardness with elongation at break ranging from 150% to 700% (14). 1C silicones can withstand temperature exposure at -75°C (-103°F) to continuous exposure exceeding 250°C (482°F) and intermittent exposure exceeding 350°C (662°F).

Flowable, low viscosity products are suitable for potting and coating applications, while medium to high viscosity products are suitable for sealing and bonding parts without adhesive run-off.

TABLE 27

Advantages and considerations of RTV silicone (1C silicone)

ADVANTAGES	CONSIDERATIONS
Very easy handling and processing	Limited cure through depth 1-3 mm/day (0.04 – 0.12 in)
Low capital investment for processing equipment	Maximum deep-section curing around 10 mm (0.4 in)
Good adhesion to a wide variety of substrates	Slow cure speeds (7-14 days total)
Available as self-levelling or non-flowable	Not paintable
Excellent temperature resistance	Silicone contamination in paint facilities

6.3.6 2C CONDENSATION CURE RTV SILICONES

A 2C condensation curing silicone formulation is a 2C pourable, spreadable, mixable or kneadable composition that reacts after mixing, typically forming a highly elastic cured material.

CURE MECHANISM

The curing of 2C condensation cure silicone is similar to that of a 1C condensation cure silicone system. However, with the 2C system, the moisture required for curing is formulated into the base compound (component A).(25) A 2C system is not dependent on atmospheric moisture to cure, making it suitable for substrate configurations where air or moisture access is limited or curing through a significant depth is required.

GENERAL CHARACTERISTICS

As by-products are released during the curing reaction, the volume and weight of the cured adhesive are reduced by approximately 3%. The overall curing time of this system can be reduced by increasing the temperature. These adhesives generally have a pot life of 5 to 45 minutes and take 15 to 90 minutes to achieve a high percentage of cure. A 2C condensation cure silicone offers similar performance to a 1C condensation cure silicone.

TABLE 28

Advantage and considerations of 2C silicones

ADVANTAGES	CONSIDERATIONS
More rapid and high deep section curing compared to 1C systems	Uniform and error free mixing is a must
Crosslinking can be slightly accelerated by increasing the temperature	Slightly higher shrinkage levels than addition cure
Relatively higher storage stability	Reversible possible, if heated in a closed container
Flowable, self-levelling or non-sag grades are available	

---

25) Room Temperature Vulcanizing (RTV) Silicones, Wacker Chemie AG, Aug. 2017, https://www.wacker.com/h/de-se/medias/7461-EN.pdf.

6.3.7 2C ADDITION CURE RTV SILICONES

Addition curing silicones are fast cure adhesives and do not require moisture or open air for crosslinking.

CURE MECHANISM

Silicone rubber compounds consist of two components: component A generally contains functional silicone polymer, while the catalyst and component B contain a functional crosslinker. When the two components are mixed, the polymer containing the catalyst and crosslinker are brought into contact with each other. During this reaction, a crosslinked matrix is formed to create the final polymer.

GENERAL CHARACTERISTICS

The average pot life of commercially available addition cure, 2C silicones typically ranges between 30 minutes and 6 hours, and can be as little as a few minutes for specialty grades. Curing can be accelerated by increasing the temperature; however, changing the mix ratio does not impact the cure speed. Unlike condensation cure systems, addition cure systems cure evenly through depth, produce a uniformly cured matrix, pose no risk of crosslinking reaction reversal at elevated temperatures and do not experience significant shrinkage.

FIGURE 173

Curing phenomenon of 2C addition cure silicones

A 2C addition cure silicone offers all the advantages of traditional silicones but with greater control over curing. It is the material of choice for automotive and medical device industries where small and complex elastomeric parts need to be produced at high speed, therefore optimising productivity.

TABLE 29

Advantages and considerations of 2C addition cure silicones

ADVANTAGES	CONSIDERATIONS
Excellent deep section cure	Prone to inhibition
Cure rate is significantly accelerated with heat	Requires correct mix ratios
No by-products, no weight loss and practically no shrinkage (<0.1%)	Once initiated, difficult to control the reaction
Pot life can be extended with the use of additives	
Will not revert to liquid once cured	

6.3.8 1C HEAT CURING SILICONES

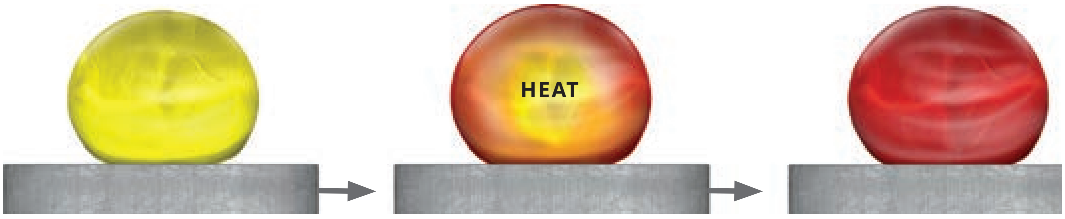
A 1C heat curing silicone contains the same composition as the 2C addition curing silicones; however, they are designed to offer an alternative solution to conventional 2C products. The 1C product usually has a shorter shelf life at ambient temperatures.

CURE MECHANISM

Heat curing silicones are cured by a specific catalyst through the hydrosilylation reaction; however, heat is required to supply sufficient energy to initiate the curing process.

FIGURE 174

Curing phenomenon of heat curing silicones



The sealant is deposited

Bulk polymerisation occurs when the sealant is exposed to a heat source

Fully cured sealant

GENERAL CHARACTERISTICS

The cure speed of 1C heat curing silicones depends solely on temperature. They are typically cured between 130°C and 200°C (266°F - 392°F). Below this range, insufficient energy is available to start the reaction, or the cure time is much longer. Whilst lower curing temperatures may result in poor adhesion, excessively high temperatures disturb the curing process and impair the properties of the cured material. To realise the final cured properties of the adhesive, careful consideration and monitoring of the curing temperature is essential.

1C heat cured silicone elastomers have the same properties as other silicones and can be made transparent for use in food and medical applications. There are few limitations regarding the customisation of 1C heat curing silicones.

TABLE 30

Advantages and considerations of 1C heat curing silicone

ADVANTAGES	CONSIDERATIONS
Low capital investment	High temperature consistent needed for curing
Suitable for short production runs	Low curing temperature may cause poor mechanical properties
Long pot life at room temperature	Difficult to control the reaction once initiated
Short curing time at elevated temperature	Curing speed cannot be altered
Excellent adhesion to many substrates	
Available as flowable, self-levelling and non-sag grades	

6.3.9 LIGHT CURE SILICONE

Light cure silicone belongs to a modern class of rubberised polymers that offer exceptionally fast cure speeds, even when compared to 2C silicone adhesives. These products now offer equivalent cure speeds to those of other light cure adhesive technologies.

CURE MECHANISM

In light cure silicone systems, two technologies are standard: radical-polymerisation and radical-polymerisation with a secondary moisture cure.

With radical polymerisation silicone elastomers, acrylate end groups are cured with free radical crosslinking of the acrylate species by the free radical photo initiator. As a free radical crosslinking reaction is susceptible to oxygen inhibition, light cure silicone adhesives need high energy intensity to achieve a tack-free surface cure, more so than for just curing through the adhesive bulk.

FIGURE 175

Mechanism of light cure silicones

A combination of radical and moisture-curing silicone adhesives may be desirable to achieve a complete cure in 'shadowed' areas of bond lines where the full intensity of the light radiation cannot penetrate. As moisture curing is the secondary mechanism, curing occurs via moisture absorption in shadowed areas. These types of dual-curing silicones exhibit excellent surface curing characteristics.

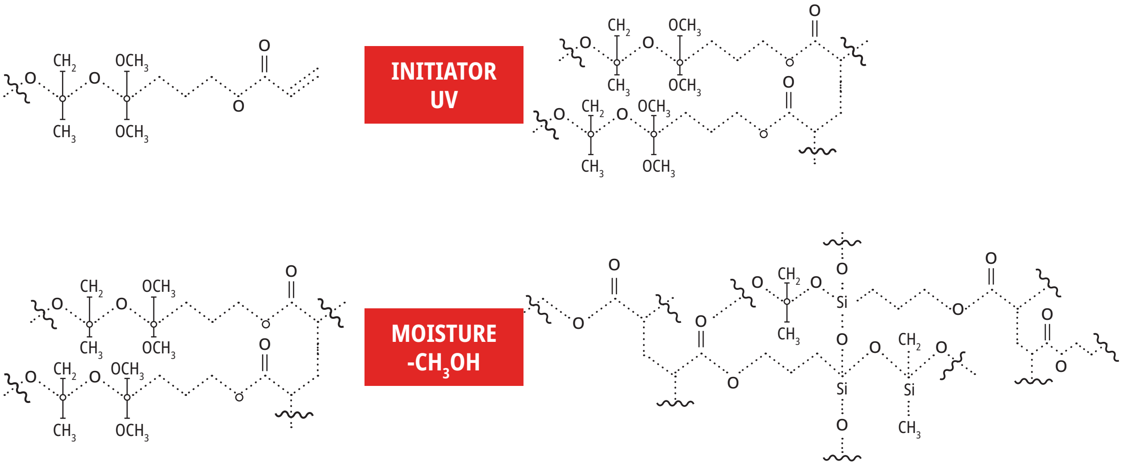


FIGURE 176

Mechanism of light-moisture cure silicones

GENERAL CHARACTERISTICS

Light cure silicones react very rapidly; the greater the light radiation intensity, the faster the silicone's curing speed. For dual-cure systems, a tack-free surface and up to 80% of its strength can be achieved in less than a minute upon exposure to UV light, with the final bond strength developing in one to two weeks depending on the substrates and environmental conditions.

Applications with large adhesive cross-sections from 5-50 mm (0.20-1.97 in) can be accommodated as the cure of adhesive is uniform from the external skin through the full depth of the adhesive bulk.(26) The mechanical properties and performance of light cure silicones are like those of other silicone adhesives.

TABLE 31

Advantages and considerations of light cure silicones

ADVANTAGES	CONSIDERATIONS
No need for cooling assemblies – reduced tooling cost	Need specialised processing setup
Cures uniformly with no shrinkage	Recommended UV lamps may vary with products
Reduced processing time – productivity	The presence of oxygen may inhibit surface cure
Low energy consumption and clean process	
No risk of scorching	

EQUIPMENT CONSIDERATIONS

One of the most relevant advantages of 1C heat curing silicone is that they can be processed without mixing equipment. They are simple to use and require no special preparation. They can be applied via standard cartridges in handheld cartridge guns or from fully automated dispensing systems utilising pails or drums. They are ideal in critical applications, where consistency and speed are prime requirements.

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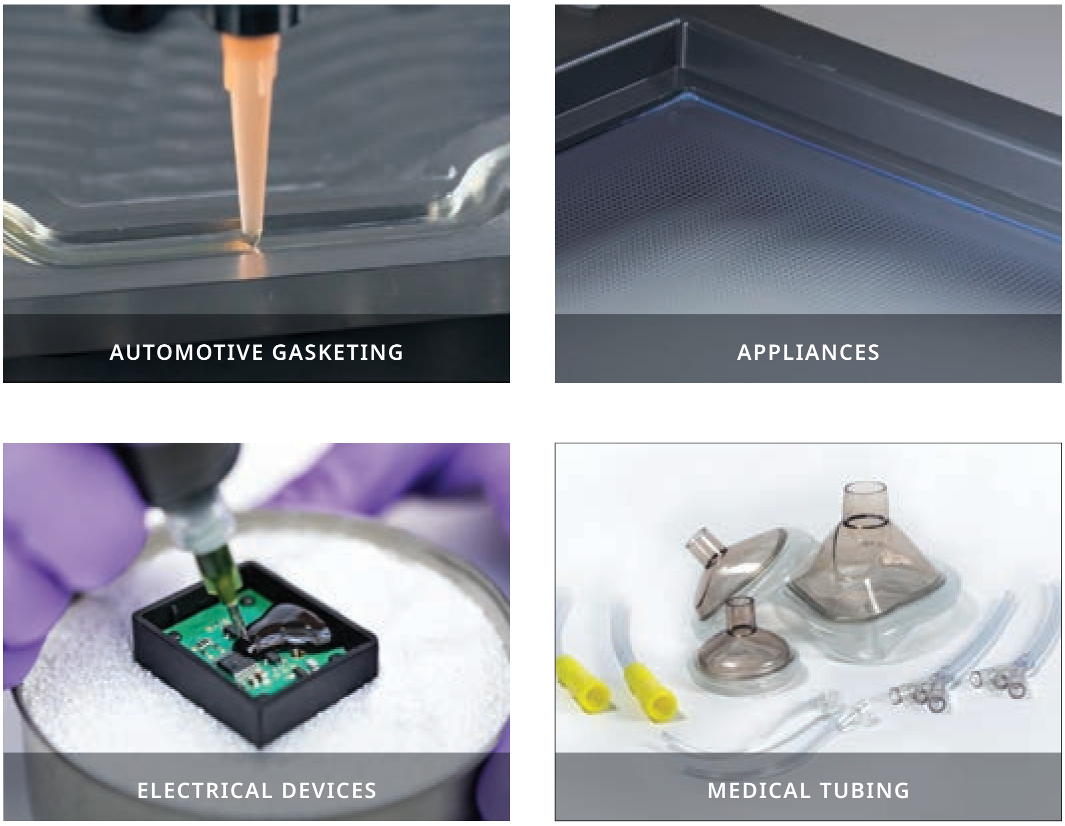
26) Elkem 2021, https://content.elkem.com/eBook-Silicone-School?utm_source=inbound%20marketing&utm_medium=website&utm_campaign=WEBSITE%20-%20Content%20Marketing.

APPLICATIONS

- Construction and industrial sealing
- Structural glazing (glass and metal frame bonding)
- Coatings
- Encapsulation and potting of electronics components
- High-performance electrical insulation
- Cushioning pads in mobile communication devices
- Electronic devices used in rugged environments
- Construction and aeronautical applications
- General high temperature, flexible bonding
- Gasketing and seals for automotive and electrical equipment
- Medical applications



AUTOMOTIVE GASKETING

APPLIANCES

ELECTRICAL DEVICES

MEDICAL TUBING

FIGURE 177

Typical applications for a variety of silicone technologies

6.3.10 BUTYL SEALANTS

Rubber sealants represent an extensive category of sealants based on the IIR and polyisobutylene contained in many formulations. Butyls are plastic (deformable) and chemically non-reactive sealants. Generally, they do not change or cure but are subject to purely physical changes of state. No chemical reaction takes place during application or within the joint.

Butyls are generally 1C elastoplastic polymeric products, and the final properties are obtained immediately after application. Generally, the product is applied and a second substrate is attached and mechanically fixed. In the case of solvent-based products, the final properties are achieved as soon as the solvent has evaporated.

Butyls are suitable for low-tech applications such as air-handling duct work, sealing machinery cabs or other limited low-tech, low-cost applications. They should not be considered for highly engineered assemblies that require reliability and strength.

6.4 STRUCTURAL BONDING

6.4.1 2C METHYL METHACRYLATE (MMA)

MMA structural adhesives are rubber toughened, 2C structural adhesives that are designed to tackle the challenges of bonding metals, plastics, composites and dissimilar substrates. MMA-based structural adhesives are designed to offer open time ranging from 3 min to 2 hours and may be used in larger gap applications up to 25.4 mm (1 in). Offering a combination of strength, toughness and ease of use, MMAs are proving their worth in numerous demanding applications in the marine, transportation and building and construction industries.

The key properties of a structural MMA adhesive are strength, toughness and flexibility. The latter is particularly important when bonding dissimilar materials with high differential flexibilities, such as rigid metal and a flexible plastic. The toughness and flexibility of an adhesive film depend on the rigidity and flexibility of the polymer and the crosslink density. Higher crosslinking leads to improved strength and chemical and heat resistance, but reduced flexibility (brittle bonds) and higher viscosity. Lower crosslinking leads to reduced chemical resistance and weaker bonds but improved flexibility.

CURE MECHANISM

The most popular and most commercially successful structural acrylic adhesives in use today are polymerisable mixtures of polymers and rubber dispersed or dissolved in MMA monomers. These adhesive products are supplied as two separate components that are primarily mixed just prior to application. Component A contains a cure initiator and component B contains a catalyst. Mixing these two components causes a reaction that starts the curing process.

GENERAL CHARACTERISTICS

One of the advantages that MMA adhesives exhibit relative to epoxies and PUs is their uniquely adjustable cure profile, which can be manipulated to provide a long open time with the much desired 'snap cure' once parts are assembled.

TABLE 32

Advantages and considerations of 2C MMA

ADVANTAGES	CONSIDERATIONS
Room temperature curing	Some odour problems
Medium and fast cure	Flammability
Good gap cure	Cold storage required
Excellent impact resistance and flexibility	Limited temperature resistance
Good flexibility at low temperature	
Substrate versatility	
Tolerant to contaminated surfaces	

EQUIPMENT CONSIDERATIONS

Most MMA adhesives are formulated in a mix ratio of 1:1, 2:1, 4:1 and 10:1 of component A (resin) to component B (activator). Because of possible odour and flammability concerns, they are commonly supplied in smaller volume dual cartridge systems with a static mixer, thus reducing potential handling issues. Dual cartridge systems are available in all the different ratios mentioned above and in volumes from 50 ml (1.69 oz) to 400 ml (13.525 oz) to be used with a manual gun or pneumatic gun options.

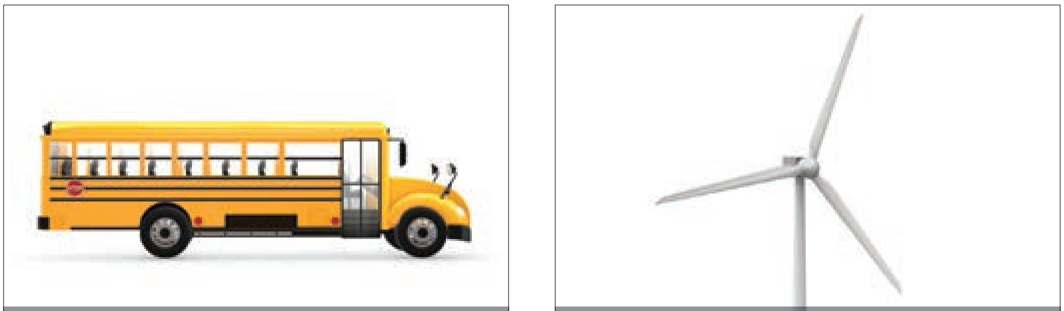
APPLICATIONS

The transportation industry, with its emerging need for maximum toughness and flexibility for bonding applications, has provided an excellent opportunity for MMA structural adhesives. These adhesives are also widely used in sophisticated electronics manufacturing, such as smartphones, and extensive area bonding applications, such as wind blade bonding applications. The following are just a few examples of applications with MMA adhesives:

- Marine market application – FRP composite deck to hull bonding, stringer to hull bonding and large gap filling
- Heavy truck assembly – metal reinforcement to composite or sheet metal bonding, roof bonding
- Automotive interior plastic bonding
- Bumper fascia assembly
- School bus assembly – structural bonding of metal reinforcement to outer body
- Electronics assembly – smart phones and laptop assembly; aluminium outer skin to magnesium frame
- Light bars for outdoor LED signs
- General bonding of dissimilar materials

SPECIALTY VEHICLES

SPAS AND HOT TUBS



SCHOOL BUSES

WIND TURBINES

FIGURE 178

Common MMA applications

6.4.2 EPOXY ADHESIVES

Epoxy adhesives are some of the most common and well-known adhesives, as they were introduced commercially in 1946 and have been used in broad applications across automotive, industrial and aerospace markets. Epoxies are probably the most versatile family of adhesives because they bond well to many substrates and can be easily modified to achieve widely varying properties.

CURING OPTIONS:	
▸2C room temperature (RT) cure	▸1C RT cure
▸1C heat cure	▸1C light cure (UV cationic)

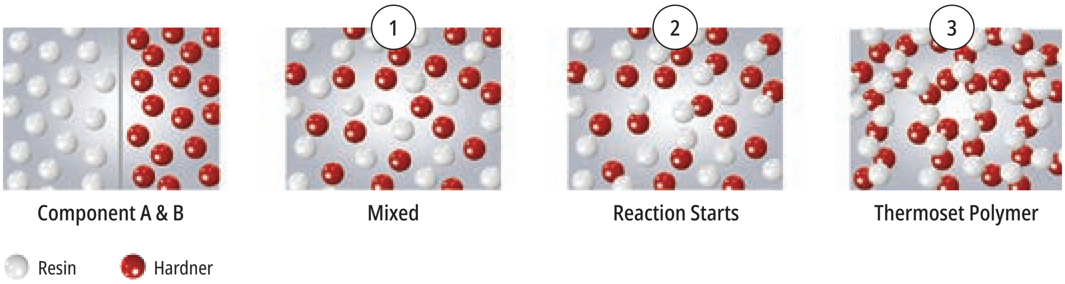
CURE MECHANISM

A 2C epoxy resin can react with various curing agents (hardeners), starting with a resin component A and a hardener component B, which have an affinity for one another and become reactive once the two parts are combined, creating polymer chains. Alternatively, 1C epoxies contain a latent hardener, which, when exposed to heat, solubilises and combines with resin to start the reaction. A crosslinked thermoset material with considerable strength and adhesion is then formed. This transformation, as previously discussed, is referred to as curing or hardening. The ability to be transformed from a liquid into a tough, hard, thermoset polymer is the single most valuable property of epoxy resins and adhesives in general.

The curing mechanism for 2C epoxies:

FIGURE 179

2C Epoxy amine reaction representation



Component A & B

Mixed

Reaction Starts

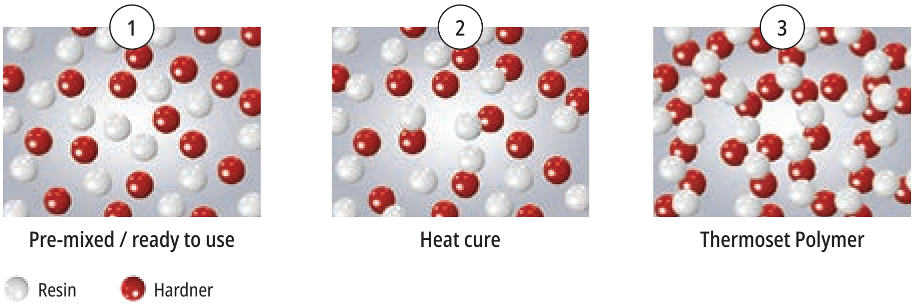
Thermoset Polymer

- **Step 1:** Solubilisation of epoxy resin with hardener when mixed.
- **Step 2:** Hardener molecule reacts with epoxy resin.
- **Step 3:** Resin-hardener intermediates attach to themselves, forming highly crosslinked thermoset polymers.

For heat cured, 1C formulations:

FIGURE 180

Cure mechanism of 1C heat cure epoxy adhesive



Pre-mixed / ready to use

Heat cure

Thermoset Polymer

- **Step 1:** Heating of single-part epoxy mixture, which allows solubilising of hardener in epoxy resin.
- **Step 2:** Hardener molecules react with epoxy resin, forming a resin-hardener intermediate.
- **Step 3:** Resin-hardener intermediates attach to themselves, forming highly crosslinked thermoset polymers.

GENERAL CHARACTERISTICS

2C, room temperature cure epoxy system

One of the distinct advantages of epoxy adhesives is that they can be cured at room temperature or at even lower temperatures. Room temperature curing epoxy adhesives are 2C adhesives, with the hardener portion and the epoxy resin portion packaged separately. This product family has a range of open and fixture times, as desired by various applications. Generally, 2C room temperature curing epoxy adhesives offers many advantages and considerations, as listed in Table 33.

TABLE 33

Advantages and considerations of 2C room temperature cure epoxy adhesives

ADVANTAGES	DISADVANTAGES
Very long shelf life of stored components at room temperature	Short working life of mixed adhesive that can result in waste, difficult application
No thermal energy required to heat either the adhesive or the parts being bonded	Components must be metered accurately and mixed thoroughly
Can be accelerated by exposure to elevated temperatures	Tensile strength, heat and chemical resistance not as high as when cured at elevated temperatures
Can be cured at room temperature to a handling strength and then exposed to elevated temperatures for final cure	Long cure times that may limit production and require fixturing
Less shrinkage and internal stress resulting from thermal expansion differences	
Moderate strength as well as heat and chemical resistance	
Lower cost due to less energy and no heating equipment	
Less hazardous (less vapour, no high temperature equipment)	

Over three distinct generations, 2C room-temperature curing epoxy adhesives have evolved from brittle to flexible to toughened. The quest for toughening was due to the inherent lack of peel and impact strength properties in brittle epoxy adhesives and the lower cohesive strength, heat and chemical resistance in flexible epoxy adhesives. The 'toughened' epoxy adhesive claims to have the following benefits: improved peel strength, greater resistance to impact and thermal shock, and the ability to absorb internal stresses in the joint without sacrificing high shear strength or temperature and chemical resistance.

1C systems

A 1C elevated-temperature curing epoxy adhesive has a hardener incorporated directly into the epoxy resin. Thus, no metering or mixing is required. However, since the curative is integrated with the resin, these systems have a limited shelf life and need refrigeration for storage. Elevated temperature curing epoxy adhesives can be desirable when the short working life of a room temperature curing adhesive cannot be tolerated. When it is necessary to eliminate measuring or mixing errors or when dispensing equipment cannot handle multicomponent systems, 1C epoxy adhesives are advantageous. Table 34 highlights some of the advantages and considerations of 1C epoxy systems.

TABLE 34

Advantages and considerations of heat curable 1C epoxy adhesive

ADVANTAGES	DISADVANTAGES
Long working life	Greater internal stresses than in room temperature curing adhesive because of: • Higher shrinkage on polymerisation • Thermal expansion coefficient differences
High temperature resistance	More brittle than room temperature curing adhesives (poorer peel and impact properties)
Good chemical resistance	Safety and hazardous nature of high temperatures
1C systems (simple, no need to mix)	1C systems have a shorter shelf life; may require refrigeration
Solid systems (film, preforms, powders) possible	Energy consumption
Viscosity decrease at elevated temperature provides more efficient wetting of substrate	Viscosity decrease of adhesive at elevated temperature could result in a starved joint

MIXING AND EQUIPMENT CONSIDERATIONS

A 2C epoxy adhesive can be packaged as a kit with a matching set of components A and B. In this method, metering is eliminated, and the container of one of the components can be used as a mixing vessel. Several well-recognised pre-portioned adhesive containers incorporate the means for mixing and dispensing – all within the same package. These include dual syringes with attachable static mixers, coaxial cartridges and pouches or divider packs with a removable hinge that can be used for spreading and mixing the product. Dual syringes with static mixers remain the most popular due to the package availability in various mix ratios, user-friendliness and overall convenience for assembling the substrates. In the case of a large application, epoxy products are available in pails or drums. While dispensing from these containers, special metering and mixing equipment are required to achieve good performance.

APPLICATIONS

Epoxies are widely used adhesives across various industry segments due to their versatility. The following is a brief list of applications:

- **Electronics adhesives** – potting and encapsulation, thermal management, solder alternatives, underfills
- **Electrical motors** – coil potting, magnet bonding, rotor/stator assembly
- **Aerospace** – stiffeners to fuselage and wing panels, helicopter blades, repair
- **Automotive** – door, deck lid, ham flanges
- **General fabrication** – marine, OEM assembly, recreational boats, racing bikes, kayaks, skis, sail boats, jet skis
- **Civil engineering** – floors, concrete repair, crack injection grouts, anchoring adhesive
- **Coatings (ambient cure)** – MRO (maintenance, repair, and overhaul) applications, automotive primers and coatings, corrosion and chemical resistant lining
- **Consumer** – DIY (do it yourself) adhesives, emergency repair putty

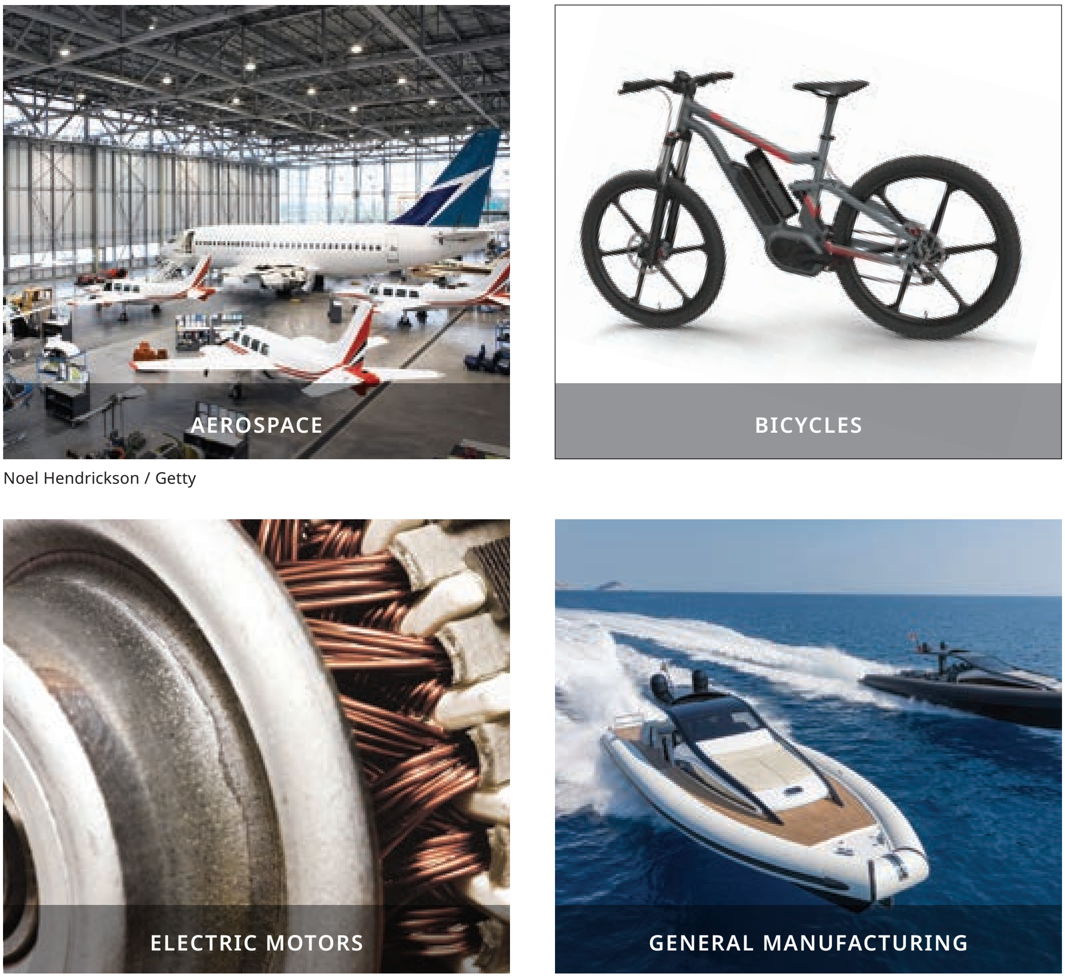


FIGURE 181

Common applications of epoxy adhesives

Noel Hendrickson / Getty

freevideophotoagency/ Shutterstock

Applications where flexible epoxy resins are valued include the following:

1. Lamination of safety glass
2. Vibration and sound dampening
3. Encapsulation of electrical components and other delicate components

6.4.3 POLYURETHANES (PUs): 1C PU AND 2C PU

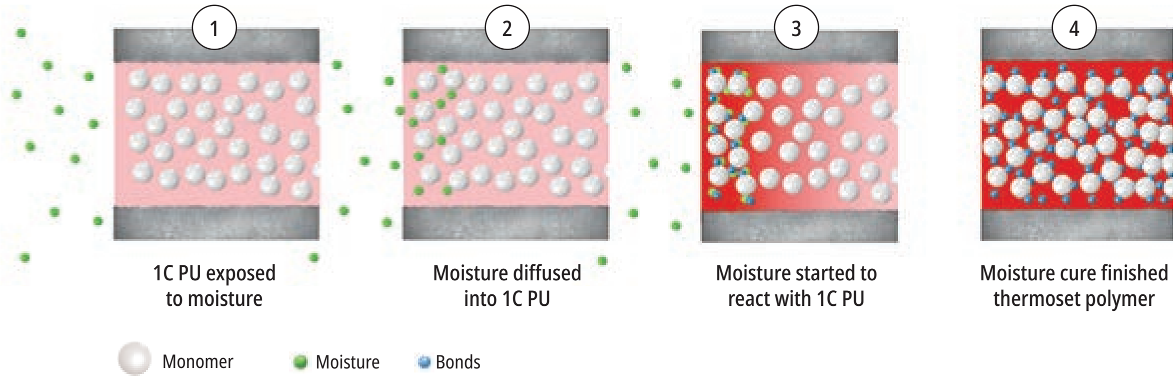
PU adhesives are supplied as 1C and 2C systems that range in viscosity from self-levelling liquids to non-slumping pastes. They cure to form thermoset polymers with good solvent and chemical resistance. They are highly versatile and can vary in cured form from extremely soft elastomers to rigid, tough plastics. PUs offer a good blend of cohesive strength and flexibility, which makes them very tough, durable adhesives. They bond well to most unconditioned substrates, but may require solvent-based primers to achieve high bond strengths. They offer good toughness at low temperatures but typically degrade in strength after long-term exposure over 150°C (302°F). Since the cure of 1C moisture-curing PUs is dependent on moisture diffusing through the polymer, the maximum depth of cure that can be achieved in a reasonable time is limited to approximately 9.5 mm (0.38 in); 2C systems, on the other hand, offer an unlimited depth of cure.

CURE MECHANISM

The majority of 1C PU adhesives react with moisture to form durable polymers. Moisture diffuses through the material, as shown in the Figure 182.

FIGURE 182

Curing steps for 1C PU



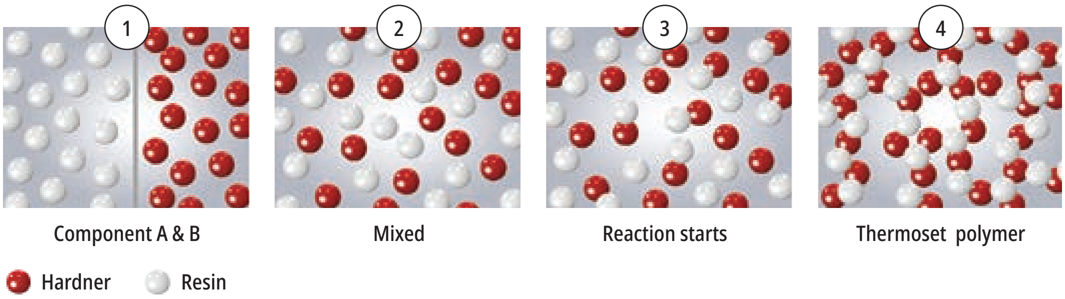
- **Step 1:** 1C PU is exposed to moisture.
- **Step 2:** Moisture diffuses into 1C PU through the skin.
- **Step 3:** Moisture starts to react with the isocyanate group (-NCO) at 1C PU chain ends.
- **Step 4:** Thermoset polymer is formed after the moisture cure is finished.

2C PU Adhesives

The 2C PU product is made from polyols and isocyanates, which are packed into two separate packages (components A and B) with a designed mixing ratio; once mixed together, polymerisation will begin.

FIGURE 183

Curing steps for 2C PU



- **Step 1:** Components A and B are separately stored in two packages.
- **Step 2:** Components A and B are mixed.
- **Step 3:** Resin (polyols) reacts with hardener (isocyanates).
- **Step 4:** Thermoset polymer is formed after curing.

GENERAL CHARACTERISTICS

Compared with 2C PU, 1C PU is more user-friendly, and it can be applied directly to substrates without further mixing. However, the product shelf life and curing speed need to be balanced for better performance. A 2C PU has a broader range of reaction speeds. The mixing ratio and package type should be well designed to guarantee performance.

Depending on the application, the key parameters for 1C PU adhesives are as follows:

1. **Viscosity:** 1C PU viscosity ranges widely from a few hundred to tens of thousands mPa.s to fit applications.
2. **Open time:** 1C PU usually has an open time in the range of minutes to hours.
3. **Initial strength:** Ranging from minutes to hours
4. **Full cure time:** 1 to 7 days

The important parameters to consider when choosing a 2C PU are the same as those discussed for other 2C adhesives.

Depending on the application, the viscosity can vary from very low to paste formulations. Temperature and humidity play important roles in 2C PU curing, with pot life and strength after curing depending on those two factors. The mixing ratio is another critical factor for bonding strength. If the ratio of hardener in component B is higher than the designed ratio, harder material will form after curing.

TABLE 35

Advantages and considerations of 1C polyurethanes

ADVANTAGES	CONSIDERATIONS
Extremely tough	Limited depth of cure for 1C PUs
Good resistance to solvents	Mixing required for 2C PUs
High cohesive strength	Primer may be needed for adhesion to some substrates
Good impact resistance	Limited high temperature use
Good abrasion resistance	

EQUIPMENT CONSIDERATIONS

A 1C PU adhesive is usually applied manually using a nozzle or spatula or by spraying. When bonding substrates without sufficient humidity or that are not moisture permeable, the required amount of moisture must be supplemented. A proven procedure is the combined spraying of the adhesive simultaneously with water in a fine mist. In the case of separate adhesive and water mist application, the water must not be sprayed onto bare metal due to oxidation concerns; rather, it should be applied on the other substrate or, ideally, on top of the adhesive. Bonding surfaces should be mated immediately after adhesive application, ensuring sufficient contact pressure while curing.

A 2C PU needs proper dispensing equipment to apply on bonding substrates. Component A is mixed with component B in a mixing nozzle and then homogeneously cured. Occasionally, heating is needed to cure or accelerate the cure speed of the adhesive.

APPLICATIONS

Widely used in big panel lamination for specialty vehicles and boats, the high-strength versions of 1C PU can also be used for structural bonding and for general purposes.

Often, 2C PU adhesives are used in large panel lamination and gap filling for boats and specialty vehicles, in durable and structural bonding for windmill blade manufacture or repair, in electronic device potting and in medical devices.

6.5 HYBRID ADHESIVES

Hybrid adhesives are a unique category of structural bonders that have been developed to significantly expand the capabilities of traditional adhesives, offer new solutions and meet new application requirements. Hybrids are 2C adhesives that combine different adhesive technologies, leveraging the best attributes of the two. These powerful combinations provide improved performance on a variety of substrates and the versatility to solve a wide range of bonding challenges.

FIGURE 184

What is a hybrid? How does a hybrid adhesive combine attributes from instant and structural bonders?

WHAT IS A HYBRID?

Cyanoacrylate Adhesive	Hybrid Adhesive	Structural Adhesive
▸ 1C ▸ Fast cure ▸ High performance on plastics ▸ Safe to handle	▸ Fast cure through high gap ▸ Universal adhesion ▸ Very good structural and environmental durability ▸ Safe to handle	▸ High gap fill ▸ Structural performance ▸ Environmental durability ▸ High performance on metals

CURE MECHANISM

Hybrid adhesives are 2C-room temperature curable compositions which have a unique patented cure chemistry that is dependent on the adhesive chemistries being combined.

For CA-epoxy hybrids, component A consists of a CA, which contains a catalyst, and component B, which contains a curable epoxy resin. Upon mixing, the catalyst initiates the curing of the epoxy component.(27) Additionally, component B epoxy may contain a CA accelerator which speeds up the cure of the CA component.(28)

For CA-acrylic hybrids, component A consists of a CA, which contains a catalyst, and component B, which contains a curable component and a transition metal. Upon mixing, the catalyst initiates the cure of the component, and the transition metal starts curing the CA component while simultaneously promoting the cure through volume.(29)

The unique cure chemistry of hybrid adhesives means these adhesives are not dependent on stoichiometric mixing and are thus more robust to variances in mix-ratio than traditional structural adhesives such as 2C epoxies or 2C acrylics.

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27) Rachel Hersee, Barry Burns, Rory Barnes, Ray Tully, and John Guthrie, Two-part, cyanoacrylate/cationically curable adhesive systems, Europe Patent EP2616520, issued February 21, 2018.

28) Emer Ward, Susan Reilly, Patricia Hedderman, Rachel Hersee, and Deborah Moore. Two-part, cyanoacrylate/cationically curable adhesive systems, Europe Patent EP2970718/US8981027, issued April 22, 2020.

29) Rory Barnes, Barry Burns, Johnathon Wigham, Rachel Hersee, and Emer Ward. Two-part, cyanoacrylate/free radically curable adhesive systems. Europe Patent EP2807224, issued May 13, 2020.

GENERAL CHARACTERISTICS

Hybrid adhesives offer universal bonding with high-quality performance in extreme environments and challenging conditions. Their features and benefits include temperature resistance up to 150°C (302°F), high-impact and vibration resistance, high moisture resistance, good environmental durability and gap-filling up to 5 mm (0.20 in). They excel at bonding various substrates, including metals, most plastics and rubbers, and they can also be used for bonding dissimilar materials. Hybrid adhesives maintain a significant advantage over high-performance (HP) epoxy adhesives when comparing fixture time, yet they are generally comparable to the fixture times of various five-minute epoxies. Hybrid adhesives are safe to handle and offer improved health and safety characteristics over traditional structural bonders, such as MMAs and even epoxies. Table 36 presents a summary of the performance attributes.

TABLE 36

Comparison of the characteristics of hybrid adhesives with other 2C adhesive types

FEATURE	PERFORMANCE ATTRIBUTE	HYBRID ADHESIVE	2C 5-MINUTE EXPOXIES	2C HP EPOXIES	2C MMAs
Productivity	Fixture Time	🟢	🟢	🔵	🟢
	Full Cure Time	⚪	⚪	⚪	⚪
Universal Bonder	Adhesion to Plastics	🟢	🔵	🔵	🟢
	Adhesion to Metals	🟢	🟢	🟢	🟢
	Adhesion to Rubbers	🟢	🔵	🔵	🔵
	Adhesion to Glass	🔵	🟢	🟢	⚪
	Adhesion to Wood	🟢	🟢	🟢	⚪
Durability	Toughness/Impact Strength	⚪	⚪	⚪	🟢
	Chemical Resistance	⚪	🟢	🟢	🟢
	Moisture Sensitivity	🟢	🟢	🟢	🟢
Safe to Handle	EH&S Ratings	🟢	⚪	⚪	⚪
	Odor	⚪	🔵	⚪	⚪

🟢 Excellent 🔵 Good ⚪ Fair

EQUIPMENT CONSIDERATIONS

Hybrids are 2C adhesives that are mixed through a static mixer nozzle with either a 1:1 or 10:1 mix ratio, depending on the product. Typically, the packs are designed for manual application, although larger packs for automated dispense have also been developed. For large packs, the automated dispense is managed through a pail pump and a pressurised reservoir system.

APPLICATIONS

Hybrid adhesives are extremely versatile adhesives that can be used in a broad range of applications. They are particularly suited to general assembly applications involving mixed substrates in a high-volume, semi-automated or manual assembly line, including applications subjected to impact loading as well as maintenance applications where instant fixture is required in variable gaps.

6.5.1

CA-EPOXY HYBRID GENERAL APPLICATIONS

- Electrical and optical goods
- Loudspeakers
- E-motors
- Gasket bonding and retaining (compound for plastic to metal)
- Lighting
- Durable goods
- Logo/label bonding, plastic/rubber-trim bonding, ID tags
- Sign bonding
- Sports equipment (especially with water exposure)

6.5.2

CA-ACRYLIC HYBRID GENERAL APPLICATIONS

- Electrical and optical goods
- Lighting
- Loudspeakers
- E-motors
- Magnet bonding (ferrite magnets)
- Handheld electrical devices, hand/power tools
- Stiffener and panel bonding
- Office furniture
- Appliances and white goods
- Sporting goods
- Post-processing for 3D-printed parts
- Composite frame bonding for RV sidewalls

6.5.3

CA-ACRYLIC 10:1 GENERAL APPLICATIONS

- Manufacturing process aid
- General maintenance and emergency repair
- Plastic tank repair
- Vehicle repair and maintenance
- Automotive interiors
- Electrical and optical systems
- Wire tacking
- General bonding
- Signage and label bonding
- Threadlocker for plastic components
- Bonding prefabricated building panels

6.6 ANAEROBIC ADHESIVES

Anaerobic adhesives were made commercially viable in 1953 by a chemist in Connecticut called Professor Vernon K. Krieble; whose single component curing formula started a new era of bonding possibilities. Initially developed as threadlockers, anaerobic formulations resulted in a new era of mechanical reliability by preventing vibrational loosening of mechanical fasteners; however, new solutions and applications were developed on this technology including thread sealants, gasketing and retaining compounds and several structural bonders.

CURE MECHANISM

Anaerobics are 1C methacrylate adhesives, which cure in the presence of metal and at the same time absence of air as oxygen acts as an inhibitor to this reaction. When exposed to two metal surfaces, oxygen is limited, thus allowing the chemical reaction to start, and the two surfaces are bonded together as the liquid adhesive polymerises.

The chemical reaction is simplified by breaking it down into four steps:

Step 1: The anaerobic adhesive is in a liquid state. The methacrylate monomers are represented by white spheres, peroxide initiator by red spheres and oxygen with blue diamonds. As long as oxygen can diffuse through the volume of the adhesive, it will remain liquid.

Step 2: When the anaerobic adhesive is applied onto the metal surface (e.g. bolt), the adhesive extracts metal ions. These extracted metal ions help decompose the peroxide initiators into highly reactive free radicals. In the presence of air, these free radicals react with oxygen and become unreactive.

Step 3: When the mating part (e.g. nut) contacts the adhesive on the first part, oxygen is no longer available.

Additionally, more reactive free radicals are generated since both metal surfaces are in contact with the adhesive. Under these conditions, the reactive radicals start reacting with monomers; they join, and the monomer becomes the free radical, which reacts with another monomer. In this fashion, monomers are added to form a growing polymer chain.

Step 4: These growing polymer chains eventually react either with another growing polymer chain, creating a crosslinked polymer network, or with other formulation components. Both reactions terminate the polymer chain growth. Thus, a very tough and durable thermoset polymer is formed.

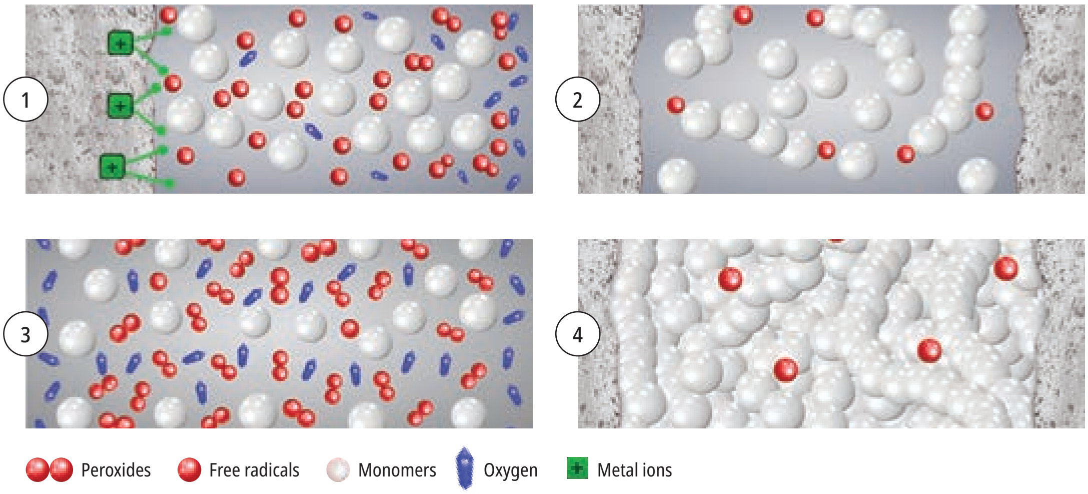


FIGURE 185

Anaerobic cure mechanism

6.6.1 THREADLOCKERS

Threadlockers are 1C liquid adhesives that completely fill the gaps between interfacing threads on nuts-and-bolts assemblies; the liquid resin changes its liquid state into solid by the contact of metal and the absence of air (anaerobic), creating an interfacial connection to prevent any loosening of the threads. It is essential that the effective length of the thread is wetted and that there is no surface contamination in the curing of the adhesive.

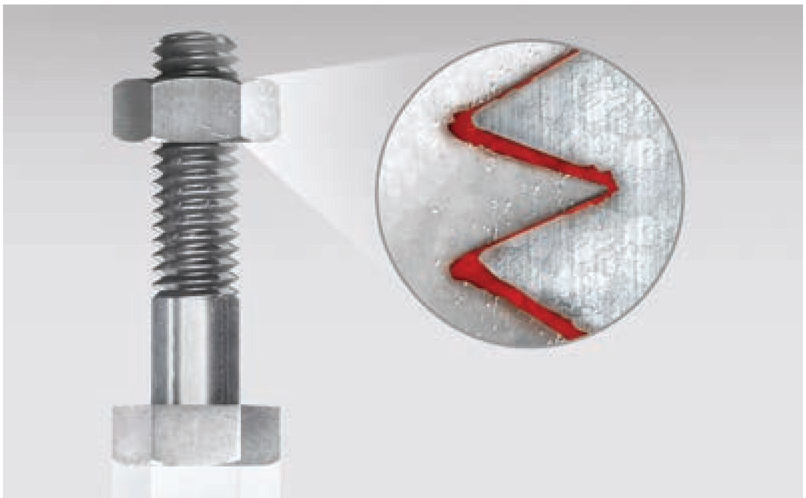


FIGURE 186

Threadlocker between the interfacing threads of a nut and bolt

Different formulas for threadlocker adhesives are available and these are classified by the torque value: removable, semi-permanent, permanent and some special characteristics like wicking grade, semi-solid formulations or pre-applied (dry film adhesive coating) for overhead applications. Recent developments are threadlockers that contain no declarable carcinogens, mutagens or reproductive toxins and thus carry no hazard symbols, risk or safety phrases.

Anaerobic threadlocker adhesives are covered in detail in the book *How to Increase Reliability and Prevent Threaded Assembly Failure* (Henkel Corporation, 2020).

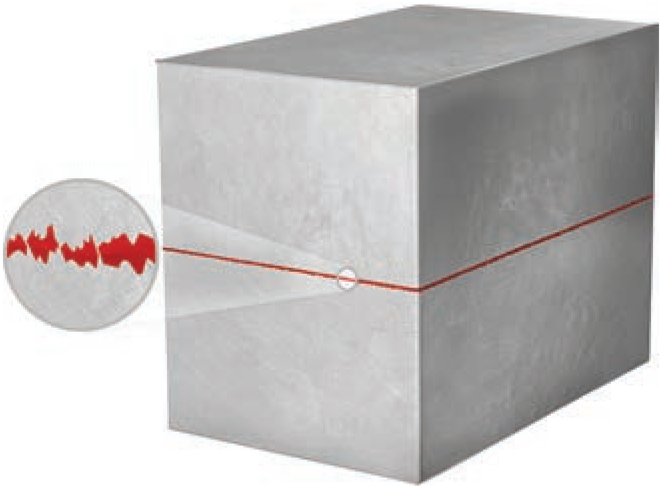
6.6.2 ANAEROBIC GASKETING ADHESIVES

These adhesives are essentially a form-in-place (FIP) liquid gasket which cures after parts are assembled. These gasket products are applied as a liquid on one part of the metallic substrate or flange joint surface; when parts are assembled, the anaerobic gasket material flows into voids, filling the gap and forming a durable seal after curing by the anaerobic mechanism.

These adhesives are used in many markets and industries. They are convenient to dispense manually, semi-automatically or automatically, and they add structural strength to assemblies, eliminate compression set and fastener loosening, and allow true unitised assembly against slip and creep.

FIGURE 187

Microscopic studies reveal that actual metal-to-metal contact between the most carefully finished interfacing parts does not exceed 25-35%. Anaerobic gasket adhesives fill 100% of the gaps



The following are some additional benefits of anaerobic gasket adhesives:

- No gasket relaxation
- No shimming
- Structural strength
- Excess material remains liquid and can be easily removed
- Accommodates poor surface finish
- No cure before assembly
- Reduce inventory costs
- Chemical compatibility
- High temperature resistance (up to 204°C (400°F))
- Easy repairability

6.6.3 ANAEROBIC THREAD SEALANTS

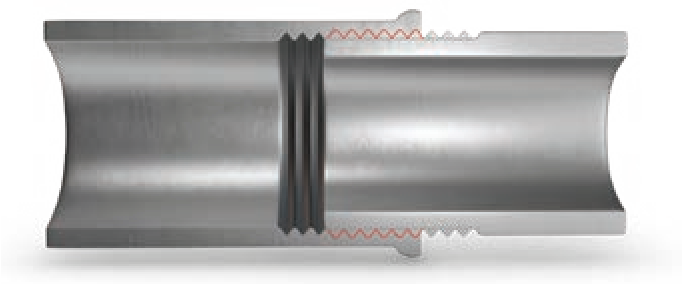
In the imperfect world of mechanical assemblies, threaded pipe components require supplementary sealants for sealing due to vibration or changes in pressure or temperature.

Threaded assemblies are designed to maintain clamp load and thus keep the two parts together. In some cases, a threaded assembly is also meant to seal in fluids or to provide an environmental barrier. Pipes are widely used to transport and store various media, such as gases and fluids, and threaded connections are often used for connecting the pipework in pressure systems. Leaks in these connections cost customers money, cause quality issues and are a potential safety hazard.

Anaerobic thread sealants seal the gap between the threads, eliminating those leaks. Consideration must be given to attributes such as easy disassembly for future maintenance, contamination-free systems, chemical resistance, temperature resistance, maximum pressure and thread type.

FIGURE 188

Anaerobic thread sealants complete geometrical seal



ADVANTAGES OF ANAEROBIC THREAD SEALANTS

- Curing when confined to threaded metal joints
- Can be used for any type of metal and any type of thread
- Seal and lock
- Suitable up to burst pressure of pipe
- Excellent chemical resistance
- No contamination inside the hydraulic system
- Re-positionable while in an uncured state

6.6.4 RETAINING CYLINDRICAL METAL ASSEMBLIES

Retaining compounds are used in circumferential assemblies with one part inserted into the other. A typical example is a bearing mounted in an electric motor housing.

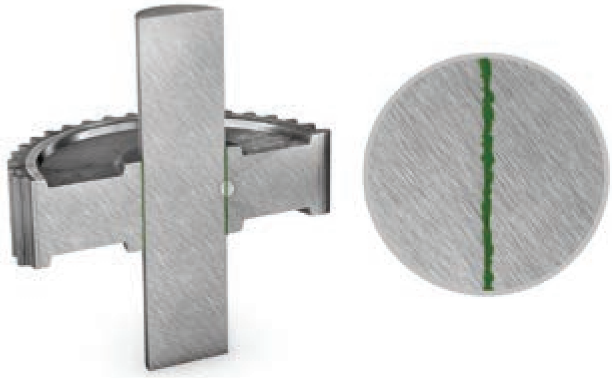
Retaining compounds achieve maximum load transmission capability with reduced interference, uniform stress distribution and no fretting corrosion. Applied as a liquid, they form a 100% contact between mating metal surfaces, eliminating the need for expensive replacement parts, time-consuming machining or the use of mechanical methods.

The major advantage of adhesives is that they require less machining tolerance and no securing parts. Following the same anaerobic curing principle, the retaining compound adhesives fill the gap between the matching parts, creating a unitised assembly and simplifying the design, production, assembly and repair of parts.

Retaining compound adhesives have excellent resistance to rotational force and can be disassembled by applying shear force.

FIGURE 189

Surface irregularities in unbonded friction fits allow actual surface contact of around 20-40% only. Contact is made at high spots only, which are easily damaged during the pressing process or by micro movements between the two surfaces after assembly



ADVANTAGES OF RETAINING COMPOUNDS

- Provide a significant increase in strength with existing geometries
- Allow lower interference achieving similar strength levels
- Lead to lower stress levels in the hub
- Enable smaller and lighter part geometries
- Allow the use of light-weight materials
- Seal the joint and eliminate corrosion

6.7 HOTMELTS

Hotmelt adhesives are 1C solvent-free thermoplastic adhesives that are solid at room temperature and have a low to medium viscosity (750 to 10,000 mPa.s) at dispensing temperatures - typically greater than 195°C (383°F). After dispensing, hotmelt adhesives rapidly cool to form a strong bond. In cooled states, hotmelt adhesives can vary in physical properties from soft, rubbery and tacky to hard and rigid. Hotmelts have excellent long-term durability and resistance to moisture, chemicals, oils and temperature extremes.

The physical forms of hotmelts are blocks, granules, candles and sticks. Hotmelts are applied by a melting machine and they set to a solid state on cooling to achieve the bonding strength. Hotmelts are usually 1C adhesives, which contain 100% solid thermoplastics. When hotmelt adhesives are used, factors such as softening point, melt viscosity, melt index, crystallinity, tack, heat capacity and heat stability must be considered in addition to the usual physical and adhesive strength properties.

Hotmelt types include pressure sensitive adhesive (PSA), non-PSA and reactive polyurethane hotmelt (PUR).

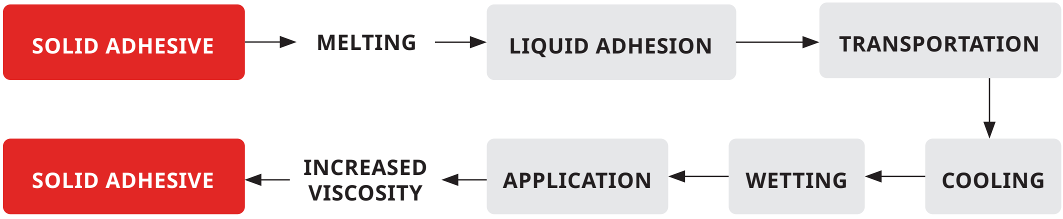


FIGURE 190

Hotmelt bonding process

GENERAL CHARACTERISTICS

A feature of hotmelts is that on cooling, they very rapidly build up their internal strength. A natural hotmelt familiar to everyone is beeswax, which bees use as a building material. Bond strengths between 1.5 and 3.5 N/mm^2 (218 - 508 psi) can be achieved with industrial hotmelts. These adhesives can be used to create thermally detachable and re-attachable bonded joints due to their adhesive characteristics.

6.7.1 POLYOLEFIN (PO) & ETHYL VINYL ACETATE HOTMELTS

PO hotmelts are made from polyolefin copolymers. By tuning the crystallinity and molecular weight of polyolefins, products with different open times and bonding strengths can be developed. Ethylene vinyl acetate (EVA) is a class of crystalline polymers with a wide range of melting points. As the weight percentage of vinyl acetate increases, the material shifts from high crystallinity to high amorphous.

Both PO hotmelt and EVA hotmelts are widely used in paper, cardboard, wood and fabric bonding. Compounded versions can be used for non-load-bearing applications up to about 70°C (158°F). EVAs and PO hotmelts represent the highest volume of hot-melt adhesives used, primarily in packaging and wood assembly applications.(30)

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30) Charles W. Paul, *Adhesion Science and Engineering.* Elsevier Science, Amsterdam, 2002.

6.7.2 POLYAMIDE (PA) HOTMELTS

PA Hotmelts are made from the condensation of dimeric acids and diamines. They are supplied in pellet form and are solid at room temperature. They have high thermal stability, high melting points and good chemical resistance to many compounds, including many common solvents, plasticisers and oils. Compared to other hotmelts, such as EVA and PO, PA hotmelts offer higher creep resistance under load and better flame retardancy and heat stability. Many grades are thermally stable up to 160°C (320°F).(31)

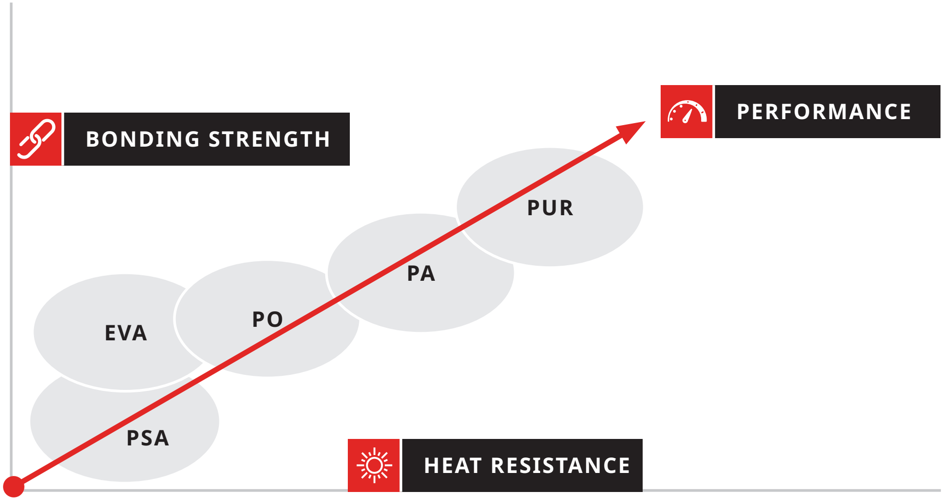

FIGURE 191

Properties of different hotmelts

EQUIPMENT CONSIDERATIONS

Hotmelts used by industry can be in the form of blocks, rods, granulate, powder and film at room temperature. They are applied to the substrate surface as a melt. The adhesive is applied by roller coating, extrusion or spraying, and bonding is carried out immediately after application or after reheating the solidified layer. Alternatively, the solid adhesive can be laid on the substrate as a film or net and then hot-pressed. In general, the bonding step requires the application of pressure.

Hotmelt adhesive is a class of thermoplastic bonding materials. The typical melting temperature for a hotmelt adhesive ranges from 65°C to 180°C (149°F to 356°F). To achieve better wetting of the substrate, it can be applied at a higher temperature, from 140°C to 220°C (284°F to 428°F); because hotmelt adhesives by their very nature melt at higher temperatures, the service temperature of a hotmelt adhesive cannot be high. The temperature resistance of hotmelt technology is the main challenge.

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31) Charles R. Frihart, 'Specific adhesion model for bonding hot-melt polyamides to vinyl,' *International Journal of Adhesion and Adhesive* (2004), Vol 24. 415-422.

The following paragraphs describe the methods of applying hotmelt adhesives in more detail.

EXTRUSION

Slot extrusion: This type of extrusion is used for applications that require a wide bonding area. Typically this method is suitable for applications on tapes and lables. The adhesive is dispensed using a slot applicator across a specified width to coat the entire substrate.

Bead extrusion: Bead extrusion pumps the adhesive through a nozzle and forms a bead-shaped adhesive amount onto a substrate. This method works well for rigid packaging applications which do not require a wide surface coverage area for case and carton bonding.

Spray: The spray application method is similar to bead extrusion; a nozzle is used to push the adhesive out. However, it also uses a stream of air that creates a swirled pattern of adhesive on a substrate. This method is beneficial for temperature-sensitive substrates, as the air helps cool the adhesive prior to reaching the substrate's surface. This method is also used for applications that need a wide bonding area but do not require much adhesive.

Roll coat: The roll coat method is used when bonding large panels together. The adhesive is metred by the gap between rolls onto the primary substrate. After adhesive is applied to a panel it moves down a conveyor, where a second panel is placed atop the first panel and then bonded together. Typically, this adhesive application method is used on panel limitations for truck and RV applications as well as garage door panels.

APPLICATIONS OF HOTMELTS

Hotmelts are used in the industry for a wide range of applications. The packaging industry (for the manufacture of packaging from paper, cardboard and sheet metal) is one of the major users. Hotmelts are also used in the printing industry for bonding the spines of books, in the textile industry for bonding appliqué and in the shoemaking industry for bonding shoe soles. The wood processing industry uses hotmelts for veneer surrounds and edging. The automotive industry employs hotmelts for a host of applications, including bonding insulating and cushioning materials, bonding headlight covers into metal frames and for wheel covers. The electronics industry also uses hotmelts.(32)

Some of the most common uses for hotmelts include:

- moulding
- packaging
- furniture
- medical
- electronic
- automotive

WIRE HARNESSES FIBRE PACKAGING

FOOD PACKAGING CONSUMER ELECTRONICS

FIGURE 192

Common applications for hotmelt technologies

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32) Janek von Byern and Ingo Grunwald, 'Biological Adhesion Systems: From Nature to Technical and Medical Application,' *Springer Science & Business Media* (2010), 198-199.

6.7.3 POLYURETHANE (PU) REACTIVE HOTMELTS

PU reactive hotmelt (PUR-HM) is another type of 1C PU adhesive. Because PUR-HM has a higher glass transition temperature and a higher crystalline component content than regular 1C PU, it needs to be heated before application. Therefore, the application process has some similarities to hotmelts.

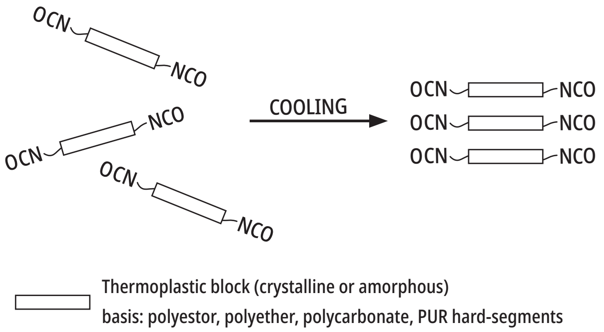
CURE MECHANISM

The setting/curing of the PUR-HM comprises two steps:

1. Component A (Isocyanate) and component B (Poly alcohol) mix when exposed to high temperatures and assume a liquid form. Once applied, the adhesive cools rapidly and solidifies to offer a holding strength like a standard hotmelt.

FIGURE 193

Hotmelt cooling process



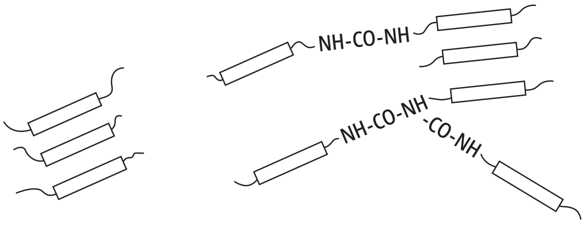
2. Once fully cooled and set, the adhesive reacts with moisture to crosslink into a highly resistant thermoset polymer, unlike normal hotmelts, which are thermoplastic in nature.

FIGURE 194

How PUR-HM works:

1. physical setting

2. curing with moisture



Crosslinking by biuret formation, entanglement during chain extension, branched polyols/polyfunctional isocyanates, physical crosslinking by hard segment domains, etc.

GENERAL CHARACTERISTICS

Key considerations in using PUR-HM for any application:

1. **Viscosity:** PUR-HM viscosity ranges widely to suit many applications
2. **Open time:** from seconds to hours
3. **Initial strength:** varies with cure conditions and demands of the application-not defined by a specific time
4. **Full cure time:** 1-7 days

As shown in Figure 196, green strength is strongly related to the bulk strength of the polymer melt. In the initial curing stage, the bonding strength is increased by crystallisation and glass transition, which are essential features of the building blocks in PUR-HM. Transition speed depends on the temperature difference between the ambient temperature and the melting temperature, and relative humidity also affects the moisture-curing speed. Proper curing conditions are critical to gain the best performance after curing.

FIGURE 195

Illustration of bond strength building up in a PUR-HM

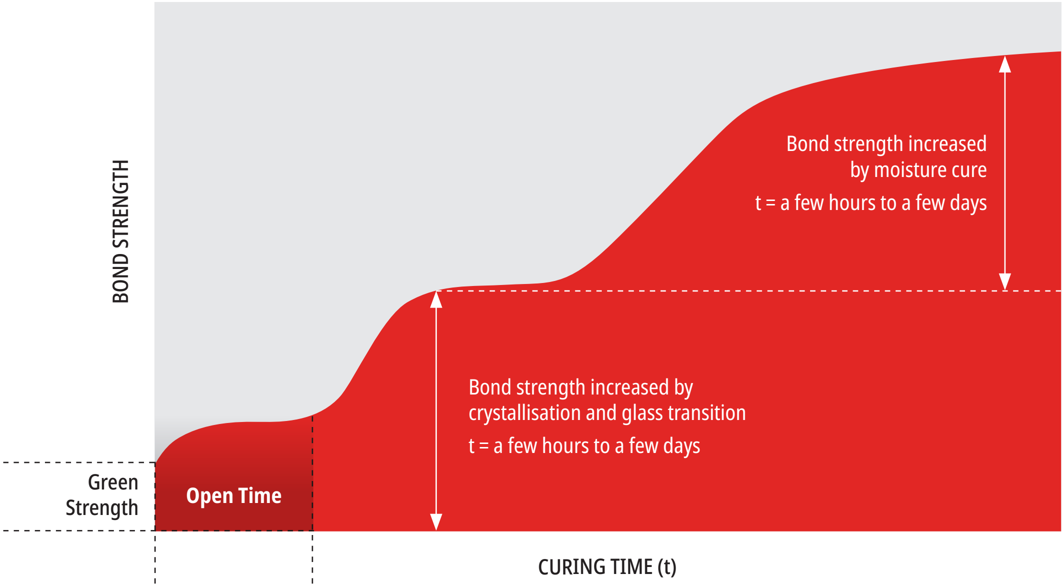


TABLE 37

Advantages and considerations of hotmelt technology

ADVANTAGES	CONSIDERATIONS
1C, solvent-free	Operator safety – hot dispense point
Unlimited depth of cure	Cool too quickly on metallic substrates
Fast fixturing	Equipment required
High adhesion	May cool too quickly on metal
Low volumetric cost	

EQUIPMENT CONSIDERATIONS

In the PUR-HM application, melting temperature and time of heating, environment temperature and humidity should be carefully considered. PUR-HM viscosity increases with heating time and temperature. The viscosity stability will affect the adhesive amount applied. The environment temperature and humidity will affect the open time, the initial strength and the final strength. The application should follow the product instructions.

Typical PUR-HM application processing equipment includes roll coaters, extrusion dispenser for bulk package, or handheld manual/pneumatic type. In the meantime, PUR adhesive can start to cure or age if it has been heated for long time or at very high temperature, so it is important to check equipment conditions.

APPLICATIONS

PUR-HM usually offer high bond strength and medium flexibility. There is significant scope within the formulation possibilities of PUR-HM for variable properties, allowing them to be modified for use as structural bonding adhesives to gap-filling sealants. They provide good initial strength and have a wide range of uses.

- electrical appliances and consumer electronics
- furniture and woodworking
- sports equipment
- panel bonding
- filter assembly
- laminations
- general bonding

ELECTRONICS APPLIANCES

FILTERS WOOD PANEL LAMINATION

FIGURE 196

Some applications of PUR-HM

6.8 SOLVENT-BASED ADHESIVES

GENERAL CHARACTERISTICS

Solvent-based adhesives are formulated with different raw material groups, including natural and synthetic rubbers and suitable resin combinations (naphthas, ketones, esters or aromatics). They are also referred to as contact adhesives. Adhesive films are formed upon evaporation of the solvents. Assemblies may be made by contact bonding (adhesive application to both surfaces) or wet bonding (applied to one of the bond faces). Most contact adhesives are based on polychloroprene rubber. They exhibit good initial strength and achieve high strength on various substrates.

The ‘trick’ for applying this type of adhesive is to use organic solvents in which thermoplastic polymers are present. The solvent content of such adhesives is generally in the 75-85% range. After application, the solvent evaporates, thus allowing the macromolecules to build cohesion and bond to the substrate.

6.8.1 SOLVENT-BASED ADHESIVE CHEMISTRIES

POLYCHLOROPRENE RUBBER (CR) ADHESIVES

CR adhesives are characterised by an immediate initial strength, which helps with fast processing or application on vertical surfaces. To ensure the highest possible initial strength, the dwell time should be until the adhesive layer is dry to the touch. The bond is formed immediately as soon as two substrates coated with a dry-to-touch film of contact adhesive are pressed together with high pressure. The adhesive will maintain its ability to form a bond upon contact for a limited time after the solvents have evaporated.

STYRENE COPOLYMER (SC) RUBBER ADHESIVES

Solvent-borne adhesives based on SC (often also called SBS or SIS adhesives) are generally applied with spray guns and are characterised by good spraying performance and relatively high solids content. For this group of adhesives, one or both substrates can be coated. A significant part of the solvents evaporates during spraying, which leads to a considerable increase in the viscosity of the adhesive. These adhesives are often used for bonding very porous substrates.

Even when applied in the thinnest layers, SC adhesives have a comparatively high contact tack during their open time. Joining the substrates while there is still a small amount of solvent in the adhesive ensures proper wetting of the bonding parts and a fast build-up of initial strength, even with low pressure or in high-tension bonding. After all the solvents have evaporated, there should be no residual tack. The bonded substrates can then be covered with fabrics or other materials, for instance, in the production of mattresses and upholstery furniture.(33)

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33) Henkel solvent based adhesive, <https://www.henkel-adhesives.com/si/en/products/industrial-adhesives/solvent-based-adhesives.html>.

POLYURETHANE (PU) SOLVENT-BASED ADHESIVES

Solvent-borne contact adhesives based on PU (or PUR) are characterised by resistance to plasticisers and good adhesion to a vast array of different materials (except bare metal). For example, they are used for bonding soft PVC parts to each other and to many other materials. Similar to CR adhesives, they can also be reactivated by heat (e.g. in vacuum deep-drawing methods for laminating formed parts with flexible top layers).

To achieve good heat and plasticiser resistances, the adhesive is usually mixed with a 3-7% crosslinking agent before processing. The immediate strength is built up by physical hardening while the final strength is achieved by chemical crosslinking (final strength after approx. 3-5 days).

EQUIPMENT CONSIDERATIONS

The performance of solvent-based adhesives is largely determined by the polymer system used in the formulation. The choice of adhesive type depends on the specific substrates and environmental resistance needed – temperature resistance, oil and plasticiser resistance, etc. Most solvent-based adhesives contain flammable solvents, which require proper precautions for safe handling. In addition, many organic solvents are regulated due to environmental concerns with emissions.

Within each type of solvent-based adhesive, formulations are available to match the application requirements of the process – brush, roll, bead, ribbon or spray. Once the adhesive is applied, the solvent evaporates relatively quickly, causing an increase in viscosity of the adhesive film. Bonds can be made immediately after adhesive application or after some solvent has evaporated, but before the adhesive has dried to the point where it will no longer wet (open time). Waiting for some evaporation prior to bonding (set time) increases the initial strength of the adhesive bond and allows assemblies to be processed more quickly.

The time window for proper bonding is specified by the adhesive manufacturer. Coating both substrates and waiting until the adhesive sets before bonding typically provides the best initial bond strength, with the longest open time. If assembly and processing require extending open time or very high initial strength, the adhesive can be coated and dried, then activated by spraying, brushing or rolling with a light coat of solvent to develop surface tack on the adhesive. Solvent-based adhesives remain soluble in organic solvent after drying. This reduces the need for equipment maintenance and facilitates clean-up. Care must be taken to follow manufacturers' recommendations for the safe handling of solvents.

APPLICATIONS

- upholstery
- assembly of pocket spring mattresses
- manufacture of foam mattresses
- speakers


FOAM LAMINATION MATTRESS MANUFACTURING SPEAKERS

FIGURE 197

Common applications of solvent-based adhesives

6.9 WATER-BASED ADHESIVE

Water-based adhesive technology is an environmentally friendly adhesive formulation. It contains no VOCs, which means that water-based adhesives are not harmful to people or the environment. They are developed using a combination of water, polymers and additives. The additives are used to impart a certain performance to the product, for example, flexibility, cold resistance (to avoid freezing at temperatures below 0°C (32°F)), wettability, tack and fast drying. These types of adhesives are ideal for porous or non-porous substrates. Water-based adhesives form a bond between two substrates once the water within the formulation evaporates or gets absorbed into the substrate, leaving the adhesive behind. This process makes them a popular choice for bonding porous substrates.

CHARACTERISTICS

Water-based adhesives contain insoluble resins which are finely distributed as solid particles in water. These adhesives form a bond as the water evaporates from the bond line, which greatly improves the resistance of the bonded joint against water and heat. These adhesives contain no solvents or other hazardous chemicals. Dispersion adhesives are applied by rollers or manual guns. The curing speed of the adhesives can be accelerated through the application of heat and air ventilation.

- eco-friendly and non-toxic
- easily recyclable
- safe to handle
- do not need to be heated before use
- easy to clean with water

6.9.1 WATER-BASED ADHESIVE CHEMISTRIES

Normally, water-based adhesives have no cure mechanism because curing is only a drying process: the product bonds when the water evaporates. There are several different chemistries – both natural-based and synthetic-based materials – which include the following:

6.9.1.1 VINYL ACETATE MONOMER (VAM) - BASED EMULSIONS (EVA OR PVA EMULSIONS)

Polyvinyl Acetate Emulsions (PVAs) are used mainly for porous substrates such as wood (furniture), board (boxes manufacturing) and lamination (corrugated board manufacturing). The product bonds in a mechanical way, penetrating into the fibre of the substrate.

FIGURE 198

(a) Board lamination

(b) Finger joint assembly

Some paper manufacturers use coatings to impart water resistance to paper. For such paper, EVA-based adhesives are more suitable than PVA-based adhesives. EVA-based emulsions are used for difficult substrates, including water resistant paper, PVC and medium-density fiberboard (MDF).

6.9.1.2 ACRYLIC-BASED EMULSIONS

FIGURE 199

Clear labels

Pressure Sensitive Adhesives (PSAs) are tacky and are mainly used for labels. It is necessary to first evaporate the water and then apply a release paper to make removing the label easier. The performance of these products is measured in terms of tack, peel and shear force. It is important to have a very clean surface before applying these adhesives. These products have a high temperature performance of around 50°C (122°F).

PSAs are ideal for the clear labels found on bottles because they are clear when dry.

6.9.1.3 NATURAL-BASED (OR BIO-BASED) ADHESIVES

FIGURE 200

For corrugated lamination natural-based products are used

These products contain raw materials derived from natural sources, such as potato dextrins. Usually, this adhesive is sold in powder form. The customer must activate the adhesive by adding water and additional additives. These products are limited to paper or boards without coatings. Normally they are rigid. Because they are derived from natural sources, they are prone to microorganism attack, making it necessary to use preservatives. They are the most cost-effective water-based adhesives, but their properties vary depending on their source.

6.9.1.4 NATURAL RUBBER (NR) ADHESIVES

NR adhesives are also called water-based contact adhesives because they are made from NR emulsified in water. These products are applied on both substrates and are allowed to sit until the water evaporates. When it is dry to the touch, the parts are bonded by applying as much pressure as possible.

FIGURE 201

a) Mattress manufacturing

b) Plastic laminated wood for kitchen furniture

6.9.1.5 LIQUID POLYURETHANE (PU)

Also known as flexible packaging, liquid PU is commonly used for food packaging. Films from different materials are bonded to create a package that preserves food; film selections are important because they need to provide the required attributes for the food product.

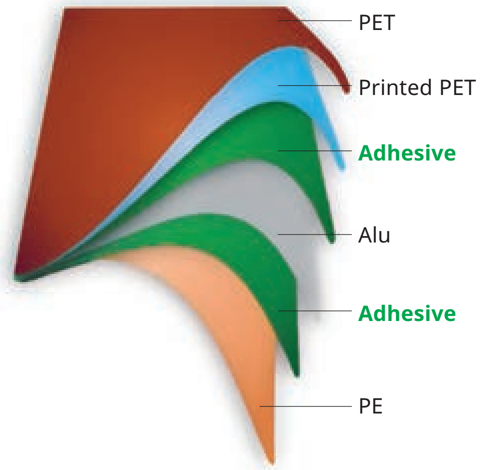


FIGURE 202

Common films bonded with liquid polyurethanes

FIGURE 203

Laminating machine

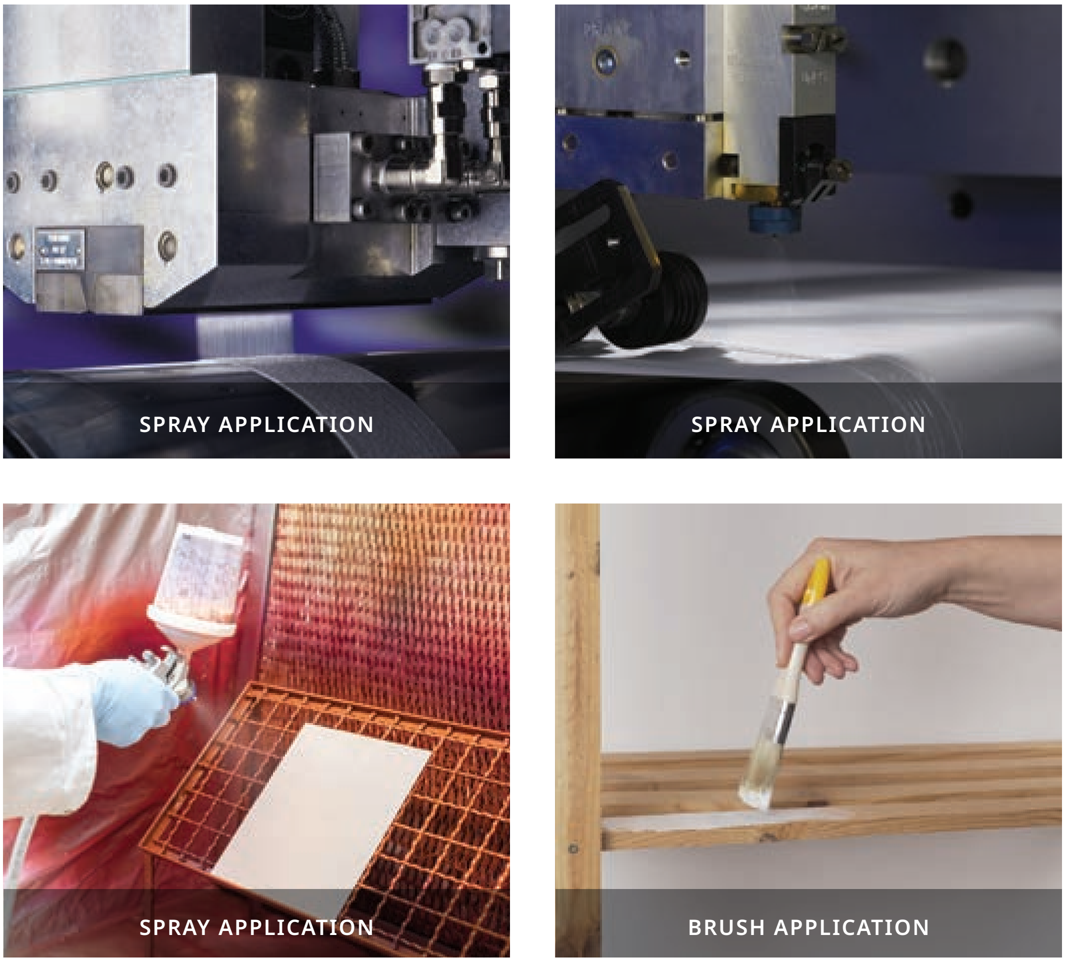
FIGURE 204

Flexible packaging examples

6.9.2 EQUIPMENT CONSIDERATIONS

Water-based adhesives are versatile and can be applied in different ways:

- spray gun
- roller
- nozzles
- nozzle activated by a pressure system
- nozzle activated by an electronic system
- manual: brush, spatula, etc.


SPRAY APPLICATION

SPRAY APPLICATION

SPRAY APPLICATION

BRUSH APPLICATION

FIGURE 205

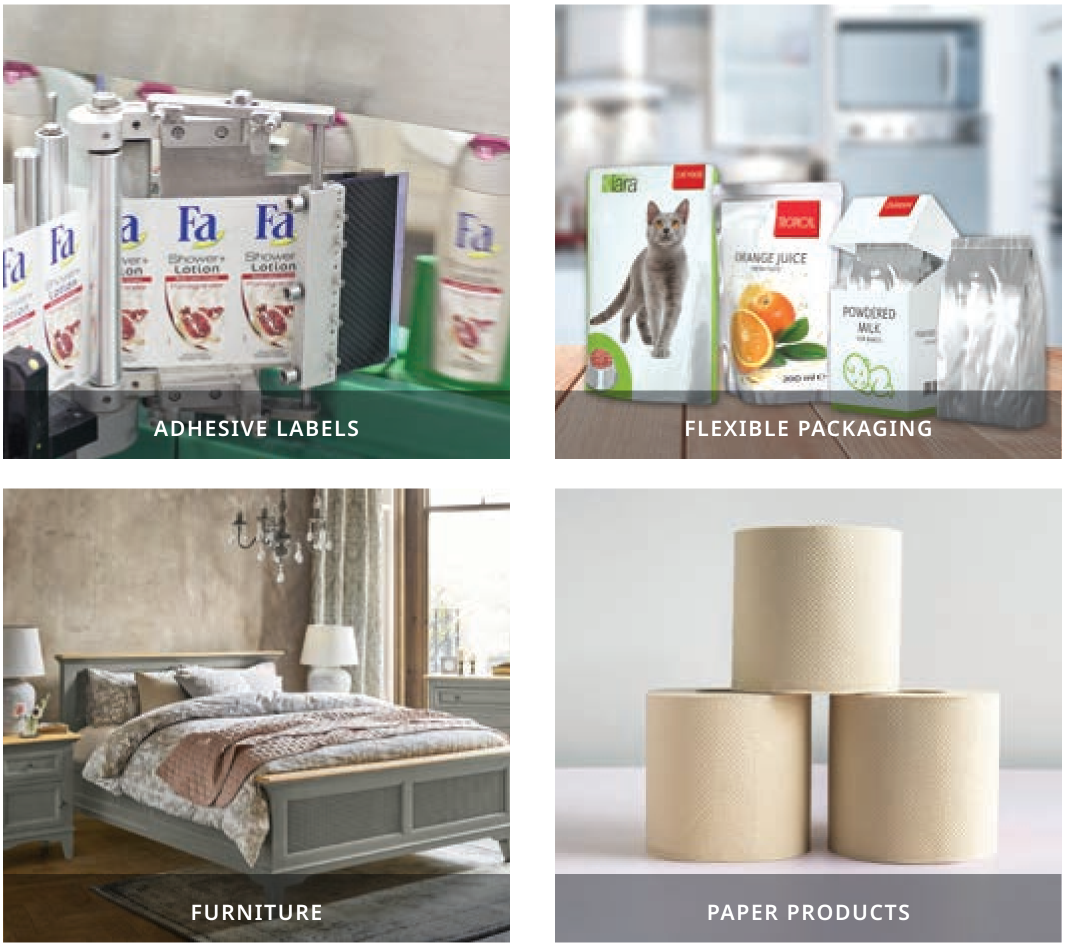
Common application systems for liquid PU adhesives

APPLICATIONS

- furniture and building
- personal hygiene
- food and beverages
- tapes and labels
- paper packaging

FIGURE 206

Common applications for water-based adhesives



Gaf_Lila / Shutterstock

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SECTION SEVEN

FAILURE MODE ANALYSIS

AS ADHESIVES ARE SELECTED FOR A PARTICULAR APPLICATION, ONE OF THE MOST IMPORTANT CONSIDERATIONS IS THE adhesive joint's environment (covered in detail in previous sections). Of course, the force acting on the joint must be capable of carrying the maximum load (without excessive creep), fatigue and cyclic stresses. Cyclic stresses, particularly slow ones, are much more damaging to an adhesive joint than steady stress. The adhesive selected for a particular application must be able to resist these loads and stresses not only initially, but also after exposure to the most severe environmental factors the adhesive joint will encounter during its lifetime. Heat and humidity are usually the most damaging environmental factors to be considered.

This section will help identify and troubleshoot the most common bonded joint challenges and failures. As discussed in Section 5, engineering a suitable assembly is not an easy task; it is important to remember that not all assemblies are created equally and that some will ultimately fail. What follows is a relatively comprehensive but generalised overview of the guidelines and steps needed for understanding possible causes of adhesive assembly failure.

Bonded assemblies are affected by how complete the contact is between the adhesive and the substrate (material), and the design should include appropriate surface preparation and the most suitable adhesive. This is the foundation of a successful bonding process. When the bonded assembly fails, we need to understand the failure mode.

7.1 TROUBLESHOOTING: FAILURE MODES

There are four different types of assembly failure modes: adhesive, cohesive, substrate and adhesive/cohesive. When analysing a failed assembly, it is essential to determine which failure mode has occurred. A thorough understanding of these failure modes will help identify the root cause of the failure, as well as contributing factors.

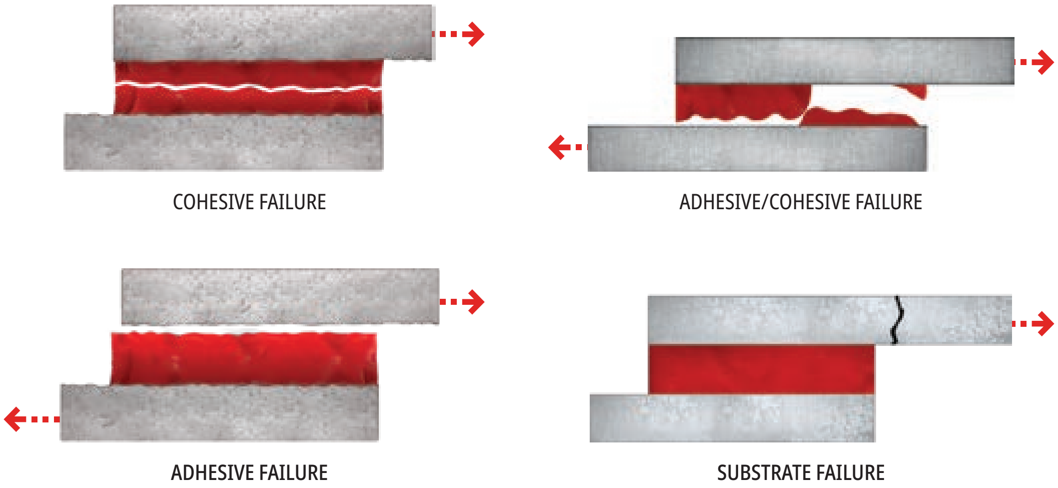

FIGURE 207

Examples of the different failure modes

7.1.1 ADHESIVE FAILURE

Adhesive failure occurs when the bonded assembly is subjected to a load that exceeds the adhesion, causing failure at the interface between the adhesive and the substrates. In this failure mode, there is visible adhesive residue remaining on one of the substrates, or it may be more localised, with each side having a piece of the adhesive layer. This localised adhesive failure often appears with adhesive segments on the two substrates mirroring each other as in Figure 209.

FIGURE 208

Adhesive failure

If this is the adhesive failure mode, a stronger bond can be achieved by reconsidering either the surface preparation or the adhesive selection.

7.1.2 COHESIVE FAILURE

Cohesive failure occurs when a fracture appears within the adhesive. In this failure mode, the adhesion strength was not exceeded, meaning that the bond between the substrate and the adhesive was not compromised; rather, the adhesive was overcome by external forces. This means that adhesion to the surface is stronger than the intermolecular bonds of the adhesive. As shown in Figure 210, the adhesive residue is visible on both substrates. This failure mode is common in uncured or insufficiently cured adhesives.

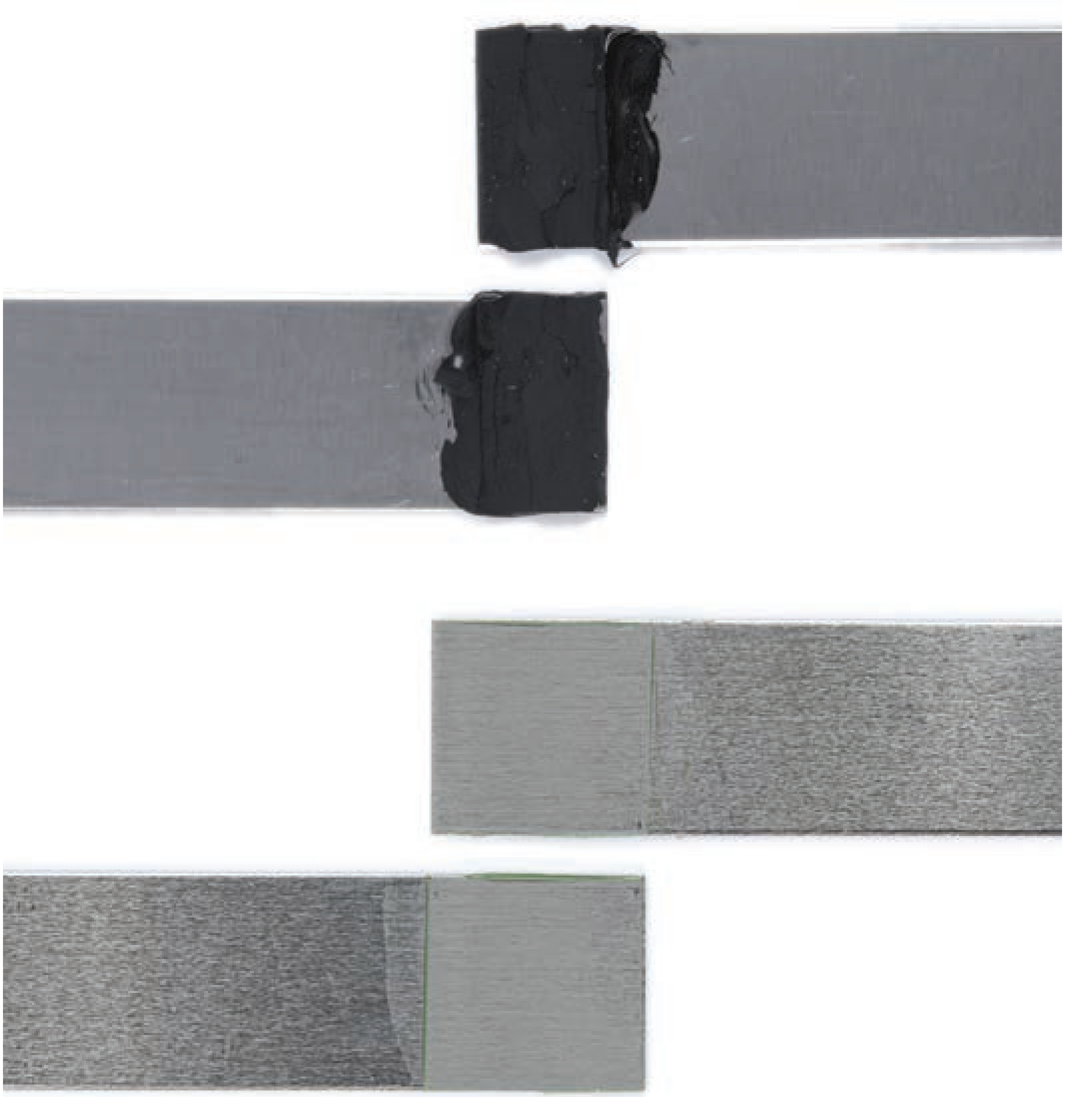

FIGURE 209

Cohesive failure on mild steel

7.1.3 SUBSTRATE FAILURE

Substrate failure occurs when external loads exceed the strength of one or the other substrates. When this happens, the substrate reaches the point of deformation and eventually its yield point, resulting in failure. This type of failure does not indicate failure of the adhesive; rather, if the external loads to which the assembly was subjected are reasonable proxies for real-world conditions, a stronger substrate is needed. Put simply, cohesion and adhesion are stronger than the substrate (in the specific dimensions and assembly).

FIGURE 210

Bonded substrates exhibiting substrate failure

Delamination is another form of substrate failure that may occur in non-homogenous substrates, such as fibre-reinforced plastics, or laminated materials, such as plywood. Alternatively, coated substrates may suffer substrate failure in the form of the coating tearing off the base material; this is most often seen with paints and other surface coatings (see Section 4).

7.1.4 ADHESIVE/COHESIVE (MIXED) FAILURE

This failure, a combination of both adhesive and cohesive failures, is normally expressed by the presence of adhesives on the bonded surface of both respective substrates. At the same time, cohesive failure will be present on both surfaces of the respective substrates. In this failure mode, the cohesive strength and adhesion strength are well balanced, resulting in a combination failure.

FIGURE 211

Adhesive and cohesive mixed failure

7.2 A PRACTICAL GUIDE TO TROUBLESHOOTING

There are many reasons why an adhesive might fail for a particular joint; therefore, while the list below is not necessarily comprehensive, at least one of the items listed is likely to be evident in any given failure.

FAILURES CAN BE CATEGORISED INTO FOUR MAIN AREAS:

1 'No Adhesive'

2 'No Cure'

3 'No Adhesion'

4 'No Performance'

7.2.1 'NO ADHESIVE'

Though this might seem obvious, it is critical that there is sufficient adhesive volume to fill the joint. Joint starvation (lack of adhesive) can often be the reason for poor joint strength (see Section 5 for gap requirements). In some applications, air voids and cavities can mean the difference between a 'good' or 'bad' joint, especially if the adhesive is required to act as a sealant as well as an adhesive.

The first step of visual inspection of a failed component is to determine the quantity of adhesive in the joint; this may be the total surface area of the bond line, which shows evidence of adhesive coverage, or the total gap fill. Visual inspection is relatively straightforward with clear components, but with opaque substrates, it can be difficult to ascertain whether the adhesive has fully filled the joint.

As some adhesives will fluoresce under UV light, this is another method that may be employed during the inspection process. UV light becomes most useful when the adhesive is a similar colour or texture to the substrate, as the UV fluorescence will highlight the presence of the adhesive.

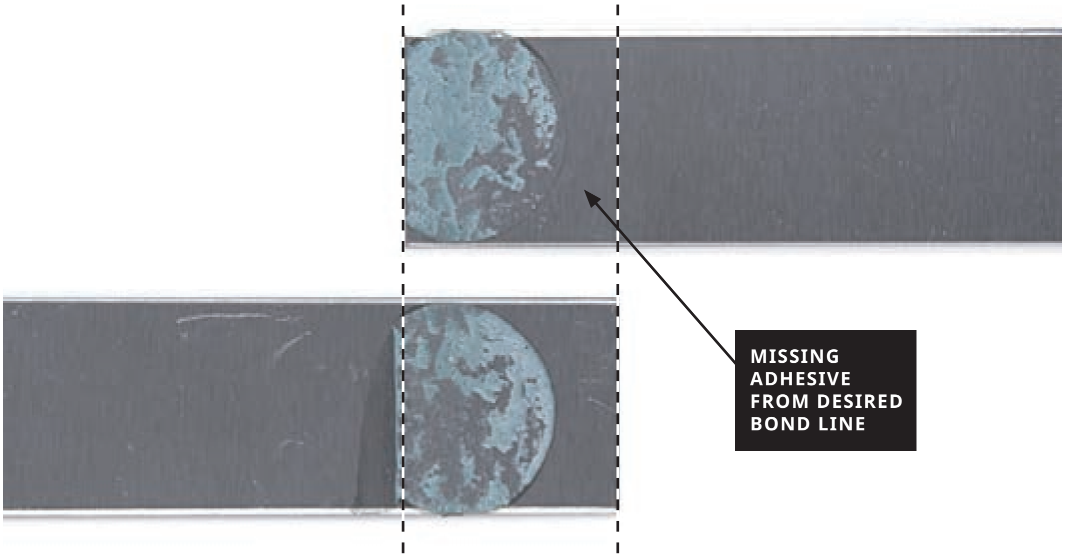

FIGURE 212

Insufficient adhesive in a designed bond line causing insufficient strength

7.2.2 'NO CURE'

Having checked for the presence of adhesive ('No Glue'), the next step is to check whether the adhesive has fully cured. This should be a relatively straightforward analysis, as uncured adhesive will be in a liquid or gel state, may be tacky to the touch or show signs of discolouration (which, in the case of 2C adhesives, may indicate insufficient mixing). This step should be relatively easy to check when the components are separated.

7.2.3 'NO ADHESION'

The third (and probably the most common) failure mode is when the adhesive does not adhere properly. This may be due to several factors, including surface contamination, oxide layers, incompatible substrates, low surface energy substrates and/or excess moisture. The general cause of this failure is a mismatch of adhesive and substrate or lack of proper surface preparation (see Section 2 for further discussion of the basics of bonding and adhesion and Section 4 for surface preparation).

7.2.4 'NO PERFORMANCE'

One of the most important requirements of an adhesive joint is its ability to retain a significant proportion of its properties under the wide variety of expected environmental conditions encountered during an assembly's service life. The factors that impact the performance, integrity and longevity of the adhesive after being fully cured, and assuming the other three factors (No Glue, No Cure, No Stick) have been addressed, are high humidity, extreme temperatures, chemical exposure, thermal cycling and UV exposure.

One of the most aggressive, hostile and damaging environments for any adhesive is the combination of high humidity and high temperature. Many manufacturers now demand performance after 1,000 hours at 85°C (185°F) and 85% RH, which is exceptionally challenging.

The durability of adhesives is the most difficult area to troubleshoot, as by its nature, it is likely to be observed quite some time after the component parts were assembled. If there are concerns that an adhesive has been subjected to environmental degradation, adhesive engineers should be engaged to assist in the analysis, as the parts may need to undergo laboratory analysis to determine the specific environmental factor or combination of factors that impacted its performance. It will be necessary to include investigations on the other three factors (No adhesive, No cure, No adhesion) when analyzing loss of performance is usually the last step of an investigation because it is the hardest to identify with certainty.

7.3

CRITICAL FACTORS WHEN SELECTING ADHESIVES

As discussed in Section 4, the following factors need to be considered when selecting an adhesive/sealant for an application. Understanding these factors is also extremely useful when examining failure modes and systematically troubleshooting the root cause of a failure.

SUBSTRATES	BOND LINE GAP	STRENGTH REQUIREMENTS
Temperature requirements	Environmental requirements	Acting forces/stressors
Processing parameters/ production quantity	Cost – adhesive and equipment	

The above guide is a starting point; conducting a comprehensive review of failure modes would require an entire book. When performing a failure mode analysis, it is always best to keep an open mind as the little details are often the most important.

Once the problem is identified, rectifying the issue may involve some of the following: altering the specification of the adhesive, modifying the surface preparation techniques, altering the application processes, changing the substrates or further training of applicators.

7.4 CONTAINMENT AND COMPLAINT DETECTIVE WORK

As part of the investigation process, several questions, such as those listed below, should be asked. An adhesives engineer may be particularly helpful in this process. Having this information prepared beforehand is important for quick resolution of the issue.

- What is the item and batch number of the adhesive?
- Has another batch product (adhesive) been tested or tried? Do both batches have the same issues? If yes, the adhesives manufacturer should be contacted immediately.
- Has the batch been quarantined? If no, quarantine the batch immediately.
- How long has it been occurring or when was it first noticed?
- Has this application/assembly ever been successful?
- How many bottles have the problem? All bottles of that batch or only a few?
- What is the failure rate: the number of parts failed vs the number of parts produced?
- How is the product stored?
- Was this bought from a distributor or direct? How is the product stored prior to order fulfilment?
- How long has this product been in use? Is this a new product or process?

7.5 THE EIGHT DISCIPLINES (8D)

An effective troubleshooting and problem-solving method that can be used to determine the root cause of failure is the 8D approach.

- Use the team approach: people with process and product knowledge and the required skills to solve the problem.
- Describe the problem: specify the customer problem in quantifiable terms – who-what-when-where-why-how-how many (5W2H)
- Implement temporary corrective actions: define and implement CONTAINMENT actions to isolate the effect of the problem until corrective action can be taken.
- Determine and verify root causes: IDENTIFY ALL potential causes that could explain why the problem occurred. Isolate and verify the root cause by testing each against the problem.
- Choose and verify corrective actions: through test programs, quantitatively confirm that the selected corrective actions will resolve the problem and will not cause new problems.
- Implement corrective actions: define and implement the best permanent corrective actions. Choose ongoing controls to ensure that the root cause is eliminated.
- Prevent recurrence: modify management systems, operating systems, practices and procedures to prevent recurrence of the problem.
- Congratulate the team: recognise the collective efforts of the team.

7.6 FAILURE MODE ANALYSIS AND TROUBLESHOOTING HELP

Troubleshooting adhesive failure can be a complex and frustrating task; however, there is always expert help available to help you overcome challenges and aid your investigation. Henkel technical specialists are a particularly valuable resource. Please reach out to your local technical helpline for further assistance.

For country specific technical support inquires, please use the contact number or email provided. For all other inquiries in countries or regions not listed please go to our global contact page.

GLOBAL

Contact Us: https://www.henkel-adhesives.com/

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SECTION EIGHT

APPENDIX

PACKAGE SIZE

Area Covered in	mm^2	cm^2	in^2
0.5 ml capsule	6,450	64.5	10.0
3 ml tube	38,700	387.0	60.0
6 ml tube	77,400	774.0	120.0
10 ml bottle	129,000	1,290.0	200.0
20 ml bottle/tube	258,000	2,580.0	400.0
25 ml syringe	316,050	3,160.5	490.0
1 oz bottle	387,000	3,870.0	600.0
50 ml bottle	635,325	6,353.3	985.0
100 ml tube	1,271	12.7	2.0
250 ml tube	3,180	31.8	4.9
300 ml cartridge	3,818	38.2	5.9
428 ml (1lb) bottle	5,521	55.2	8.6
850 mL cartridge	10,772	107.7	16.7
1,000 mL bottle	12,707	127.1	19.7

Note: based on a 0.076 mm (0.003 in) bondline thickness

PRIMERS, ACTIVATORS, MISCELLANEOUS

Area Covered in	mm^2	cm^2	in^2
1 oz bottle	580,500	5,805.0	900.0
2 oz bottle	1,161	11.6	1.8
40 g spray can	774	7.7	1.2
6 oz spray can	3,344	33.4	5.2
32 oz (quart) can	18,576	185.8	28.8
1 gal can	74,304	743.0	115.2
4 g mixer cup	7,740	77.4	12.0
4 oz mixer cup	322,500	3,225.0	500.0
12 oz spray anti seize	1,871	18.7	2.9
1 lb brush tip anti seize	516,000	5,160.0	800.0
16 oz equip. flush solvent	9,288	92.9	14.4
1.2 oz metered mist	645	6.5	1.0
18 oz chisel spray	5,805	58.1	9.0

Note: based on a 0.051 mm (0.002 in) wet film thickness

Viscosity mPa.s (cP)	Drops per ml	Drops per lb bottle
1-100	100	42,800
100-1,000	70	29,960
1,000-5,000	50	21,400
5,000-10,000	30	12,840

UNIT CONVERSION TABLE (IMPERIAL/METRIC)

DIMENSIONS	WRITTEN OUT	SI SYMBOL	MULTIPLICITY	ENGLISH OR C.G.S	MULTIPLICITY	TO GET SI
Length	metre	m	x 3.281 =	feet (ft)	x 0.305 =	m
	millimetre	mm	x 0.039 =	inch (in)	x 25.400 =	mm
Force	newton	N (kg.m/s^2)	x 0.225 =	pound-force (lbf)	x 4.448 =	N
Mass	kilogram	kg	x 2.204 =	pound (lb)	x 0.454 =	kg
Pressure Stress	megapascal	MPa (N/mm^2)	x 145.038 =	pound-force (lb-in^2) per square inch	x 0.007 =	MPa (N/mm^2)
Area	square metre	m^2	x 10.764 =	square feet (ft^2)	x 0.093 =	m^2
	square centimetre	cm^2	x 0.155 =	square inch (in^2)	x 6.452 =	cm^2
Torque	newton metre	Nm	x 0.738 =	pound foot (lb-ft)	x 1.356 =	Nm
	newton metre	Nm	x 8.851 =	pound inches (lb-in)	x 0.113 =	Nm
Volume	litre	l (dm^3)	x 1.057 =	(liquit) quart (Imp.qt.)	x 0.946 =	l
	litre	l (dm^3)	x 33.814 =	US ounce (oz)	x 0.030 =	l
	litre	l (dm^3)	x 0.220 =	gallon (Imp. gal.)	x 4.546 =	l
	litre	l (dm^3)	x 2.113 =	pint (Imp. pt.)	x 0.473 =	l
	litre	l (dm^3)	x 61.024 =	cubic inch (in^3)	x 0.016 =	l
	millilitre	ml (cm^3)	x 0,061 =	cubic inch (in^3)	x 16.387 =	ml
Density	gram/cubic centimetre	g/cm^3	x 0.362 =	pound per (lb/ in^3) cubic inch	x 27.680 =	g/cm^3
	gram/cubic centimetre	g/cm^3	x 62.400 =	pound per (lb/ ft^3) cubic feet	x 0.160 =	g/cm^3
Angle	radian	rad	x 57.296 =	degree (°)	x 0.017 =	rad

Viscosity	dynamic	pascal seconds	Pa.s	x 1,000 =	centipoise (cP)	x 0.001 =	Pa.s
	kinematic	square metre/ second	m^2/s	x 10,000 =	stokes (St)	x 0.0001 =	m^2/s

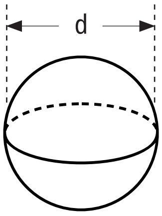
USEFUL MATHEMATICAL CALCULATIONS

- Weight to Volume: Weight (g) ÷ Density (g/cm^3) = Volume (cm^3)
- Volume to Weight: Volume (cm^3) x Density (g/cm^3) = Weight (g)

AREA COVERAGE:

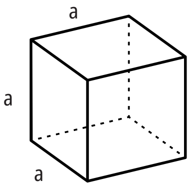
- Length = L Width = W Bondline Thickness = BT Diameter = d Radius = r Potting Depth = PD
- All dimensions in mm
- For no induced gap, make the Bondline Thickness 0.025 mm
- Flat Parts: [L x W x BT] / 1,000 = Requirement in ml per part
- Non-threaded Cylindrical Parts: [d x L x BT x π] / 1,000 = Requirement in ml per part
- Cylindrical Potting/ Encapsulating Applications: [π x r^2 x PD] / 1,000 = Requirement in ml per part

SPHERE



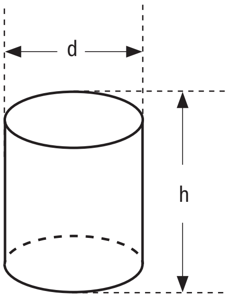
$$V = \frac{\pi d^3}{6}$$

CUBE



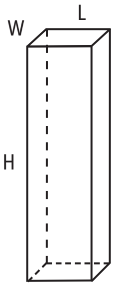
$$V = a^3$$

CYLINDER



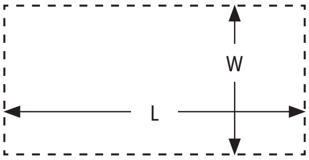
$$V = \frac{\pi d^2 h}{4}$$

RECTANGLE PRISM



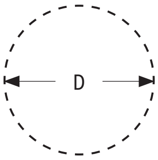
$$V = L x W x H$$

RECTANGLE



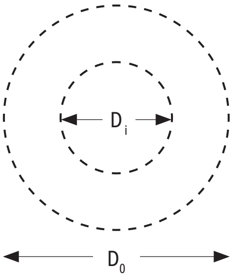
Volume = L x W x bondline gap

CIRCULAR



Volume = $(\pi (D)^2/ 4)$ x bondline gap

ANNULAR



D_i = inner diameter

D_o = outer diameter

Volume = $(\pi (D_o^2 - D_i^2) / 4)$ x bondline gap

SECTION NINE

BIBLIOGRAPHY

A. Kass, F. Wangaard and H. A. Schroeder. *Chemical Degradation of Wood: The Relationship Between Strength Retention and Pentosan Content*, Wood and Fiber Science, Issue Number 1 / Spring 1970.

A. Pizzi, and K. L. Mittal. *Handbook of Adhesive Technology,* M. Dekker, 2003.

Austerberry, Michael. *'Silane-Modified Polymers (SMP) Combining the Best of Silicone & Organic Polymers.'* International Silicone Conference –May 17, 2016. 2016. 1-25.

Brune, Kai & Dieckhoff, Stefan & Fricke, Holger & Groß, Andreas & Haag, Katharina & Hartwig, Andreas & Cavalcanti, Welchy & Mayer, Bernd & Noeske, P.-L & Wilken, Ralph. (2020). Circular Economy and Adhesive Bonding Technology Study by the Fraunhofer Institute for Manufacturing Technology and Advanced Materials IFAM (B. Mayer, A. Groß; eds.). 10.24406/ifam-n-603186.

Canadian Centre for Occupational Health and Safety, 2008, Corrosive Materials – Hazards, www.ccohs.ca/oshanswers/chemicals/corrosive/corrosiv.html, 6th May 2021.

'Carriage Bodies and Parts,' The Carriage Monthly, April 1911, p. 20.

Charles R. Frihart, 'Specific adhesion model for bonding hot-melt polyamides to vinyl,' *International Journal of Adhesion and Adhesive* (2004), Vol 24. 415-422.

Charles W. Paul, *Adhesion Science and Engineering. Elsevier Science,* Amsterdam, 2002.

Chris Rockett, LightSources, Inc., *'UV Degradation Effects in Materials – An Elementary Overview,'* UVSolutions (2019), accessed May 7, 2021, uvsolutionsmag.com/articles/2019/uv-degradation-effects-in-materials-an-elementary-overview/.

Curbell Plastics, *Selecting Plastic Materials for Use in Chemical Environments*, www.curbellplastics.com/Research-Solutions/Resources/Articles/Plastic-Materials-in-Chemical-Environments#:~:text=In%20chemical%20attack%2C%20a%20reaction,chain%20will%20have%20reduced%20entanglement, 6th May 2021.

Edward M. Petrie, *Handbook of Adhesives and Sealants,* McGraw-Hill, 2007.

Elkem 2021, https://content.elkem.com/eBook-Silicone-School?utm_source=inbound%20marketing&utm_medium=website&utm_campaign=WEBSITE%20-%20Content%20Marketing.

Emer Ward, Susan Reilly, Patricia Hedderman, Rachel Hersee, and Deborah Moore. Two-part, cyanoacrylate/cationically curable adhesive systems, Europe Patent EP2970718/US8981027, issued April 22, 2020.

Henkel solvent based adhesive, <https://www.henkel-adhesives.com/si/en/products/industrial-adhesives/solvent-based-adhesives.html>.

https://www.antala.uk/wp-content/uploads/2016/07/Dow-Corning_Selector-Guide_AntalaUK_digital.pdf.

International Organization for Standardization, 'ISO 4587 Adhesives - Determination of Tensile Lap-Shear Strength of High Strength Adhesive Bonds,' 2003.

Janek von Byern and Ingo Grunwald, 'Biological Adhesion Systems: From Nature to Technical and Medical Application,' *Springer Science & Business Media* (2010), 198-199.

Jayashree Salla, Krishna K. Pandey, Kavyashree Srinivas, 'Improvement of UV resistance of wood surfaces by using ZnO nanoparticles,' *Polymer Degradation and Stability,* 97, no. 4 (2012).

Joe Mausar, *'On the Surface - Surface Energy and Surface Tension,'* Adhesives and Sealants Industry, 2010.

Loctite North America. *Worldwide Design Handbook.* Rocky Hill: Loctite European Group and Loctite North America, 1998.

Proebster, Manfred. Industrial sealants. Landsberg am Lech, Germany: Verlag Moderne Industrie, 2004.

Proebster, Manfred. Industrial sealants. Landsberg am Lech, Germany: Verlag Moderne Industrie, 2004, 37.

Proebster, Manfred. Industrial sealants. Landsberg am Lech, Germany: Verlag Moderne Industrie, 2004, 37-40.

Nelson K. Akafuah, Sadegh Poozesh, Ahmad Salaimeh, Gabriela Patrick, Kevin Lawler, and Kozo Saito, *Evolution of the Automotive Body Coating Process—A Review.* Mechanical Engineering Faculty Publications. 25. 2016.

Petrie, Digital Engineering Library; digitalengineeringlibrary.com, 280-281, McGraw-Hill, 2000.

Rachel Hersee, Barry Burns, Rory Barnes, Ray Tully, and John Guthrie, Two-part, cyanoacrylate/cationically curable adhesive systems, Europe Patent EP2616520, issued February 21, 2018.

R. B. Seymour et al., *Structure – Property Relationships in Polymers* (New York: Plenum Press, 1984).

Room Temperature Vulcanizing (RTV) Silicones, Wacker Chemie AG, Aug. 2017, https://www.wacker.com/h/de-se/medias/7461-EN.pdf.

Rory Barnes, Barry Burns, Johnathon Wigham, Rachel Hersee, and Emer Ward. Two-part, cyanoacrylate/free radically curable adhesive systems. Europe Patent EP2807224, issued May 13, 2020.

R, Tang Y and Tsiang, 'Rheological, extractive and thermal studies of the room temperature vulcanized polydimethylsiloxane,' *Polymer*, 1999, 6135–6146.

S. Ebnesajjad, Handbook of adhesives and surface preparation, *Technology, Applications and Manufacturing* (2011).

Six Big Losses, https://www.oee.com/oee-six-big-losses.html#equipment-failure.

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