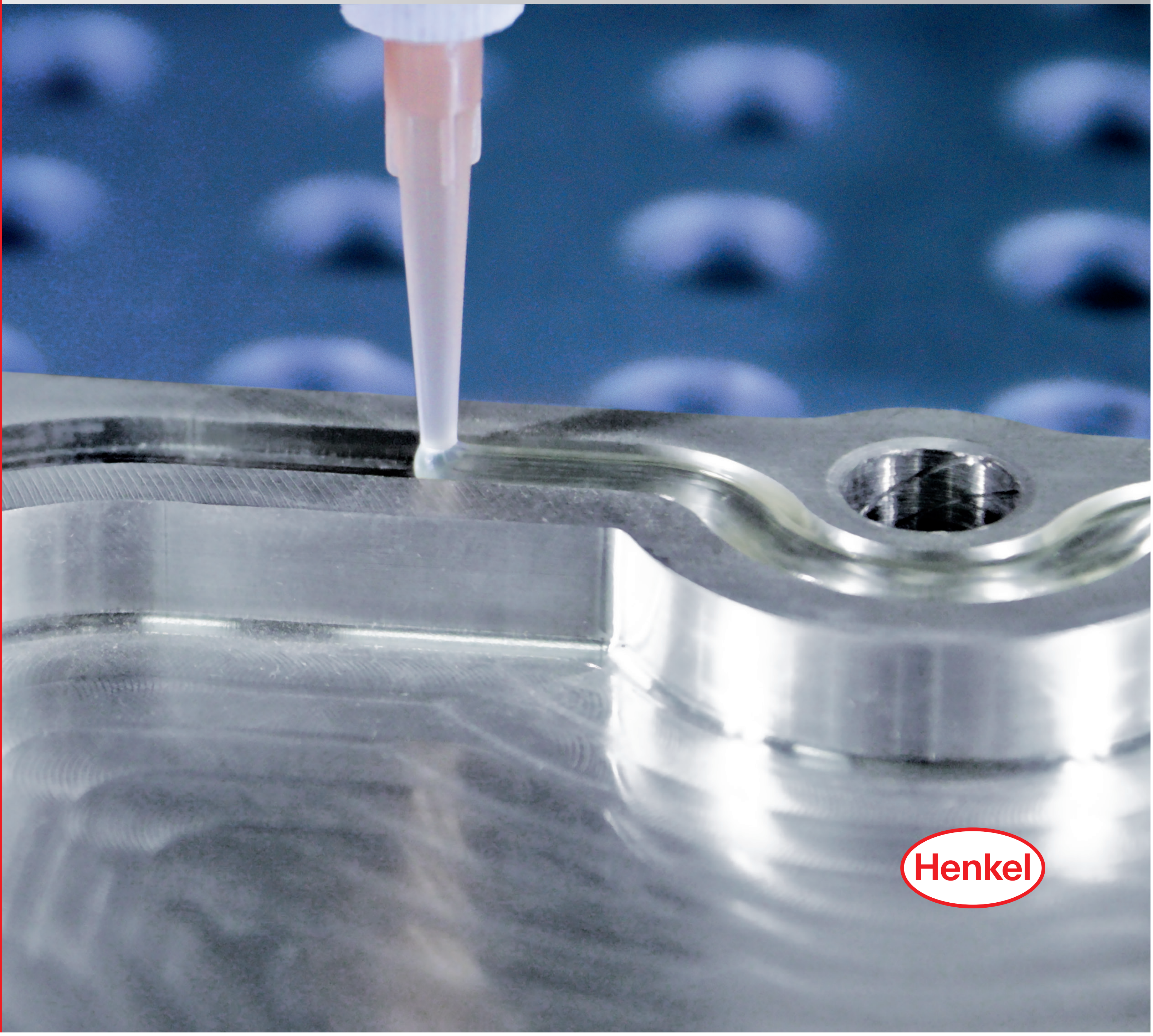
Worldwide Sealing Guidelines for Cured-In-Place Gaskets



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1. Introduction

In order to improve fuel economy and comply with environmental regulations, a growing number of systems operate with higher torque capacity, smaller packages (lightweight design) and at higher temperatures. In addition to this, automation, costs and traceability are becoming important requirements that cannot be ignored during the development phase. The combination of these factors increases the difficulties to design zero-leak joints.

To ensure that the requirements are met, it is essential to design the bolted joint following gasket-specific guidelines. The intention of this document is to provide general design considerations that are independent of the type of gasket and specific guidelines for Cured-In-Place Gaskets (CIPG). These design guidelines are based on results of several trials, the analysis of gasketed joints, experience and the results of analytical and numerical calculations performed at Henkel.

The general design considerations described in Section 3 summarize the knowledge gained from three projects at the University of Stuttgart, sponsored by the German Research Association for Drive Technology (FVA-Forschungsvereinigung Antriebstechnik), in which Henkel is an active partner.

2. Definitions

Seals are classified as static or dynamic, depending on whether the sealed parts move relative to each other. A rotating shaft in a housing is an example of a typical dynamic system. While flanges are classified as static systems, they encounter small "micro-movements" because of vibration, temperature changes, pressure changes, shock, impact or transmitting loads.

A static seal or gasket is a material positioned between two flanges that are held together by fasteners to prevent leakage of fluids and/or gases by closing the gaps between these surfaces. In order to keep the sealing function and a leak-free joint for a prolonged time, the gasket must be resistant to the medium being sealed and able to withstand the application temperature, pressure and micro-movement of the joint.

The static gaskets or seals are categorized as shown in figure 1.

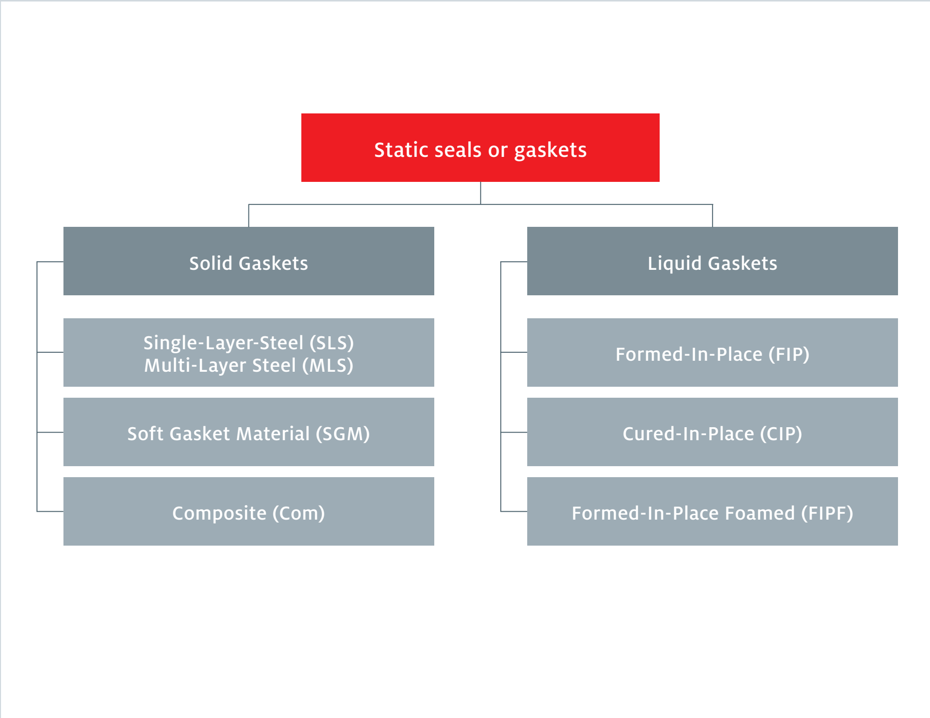


Figure 1: Gasket types.

Henkel's product portfolio belongs to the group of liquid gaskets and is organized as follows:

Formed-In-Place Gaskets (FIPG): These gaskets are formed by screen-printing or by applying a bead of liquid elastomer or anaerobic sealant onto one of the flanges to be sealed. The flanges are assembled in the uncured state, making the sealant spread between the flanges and forcing it into the surface imperfections to provide total contact between the two faces. After assembly, the material cures to form a durable seal. The sealing function is performed by adhesion of the sealant to the mating flanges.

Cured-In-Place Gaskets (CIPG): These gaskets are formed by applying a bead of liquid elastomer that is cured before assembly. These gaskets are dispensed onto a groove or step using automated high-precision equipment, generating a uniform solid compression gasket. The material is cured immediately after dispensing either by ultraviolet (UV) light, by heat or through a multi component system. The cured gasket adheres to the applied flange and, when assembled, is compressed between the mating parts, thereby closing the existing gaps. Sealing is achieved through compression of the cured gasket during flange assembly, similar to SGMs.

Formed-In-Place Foamed Gaskets (FIPFG): These gaskets are formed by applying a bead of liquid elastomer onto one of the flanges to be sealed, which will be foamed either by a neutral gas or by gases released by the reaction of two components during the dispensing process. Depending on the process, the resulting gasket will have either open cells, mixed cells or closed cells. The material is cured after dispensing either by ultraviolet (UV) light, by heat or through a multi-component system. The cured gasket adheres to the substrate flange and, when assembled, is compressed between the mating parts, thereby closing the existing gaps. Sealing is achieved through compression of the cured gasket during flange assembly, similar to CIPGs.

2.1. Compression gaskets

A system sealed by compression will be tight when the minimum compression will result in the minimum sealing force/pressure and the maximum compression will not exceed the elastomer's strain limit. Consequently, this leads to an opti-mal sealing compression range that should be considered while designing flanges with CIPG, FIPFG or SGMs.

Hence, the bead geometry is a very important characteristic of CIP gaskets. The height and width of the bead and the groove/step must be adjusted according to specific guidelines to suit the application conditions and mating flanges.

The bead dimensions must be defined considering both the tolerance stack-up analysis of the mating flanges and the void volume inside the groove/step.

The tolerance stack-up analysis should enable the calculation of maximum and minimum gaps to be sealed due to the poten- tial accumulated tolerances of the assembly. It will directly influence max and min compression and define the heights of both the bead and the groove/step.

The void volume calculation will give information about the available space for the gasket to expand thermally, be compressed and swell, without leading to over-strain. It will define the width of the bead and the groove/step.

To provide good sealing performance, CIP gaskets, like other compression gaskets, need to fulfill a series of requirements, such as:

- keep main characteristics when in contact with the fluid to be sealed at the application temperature (media compatibility, suitable temperature range)
- conform to the surface imperfections of the mating flange and handle flange motions (compressibility, recovery and shear strength)
- retain minimum sealing force (low relaxation)
- resist damage caused by flange compression forces and internal pressure (compressive and tensile shear strength).

In order to avoid premature sealing failure due to system concept, this guideline will cover not only the bead geometry, but also give general recommendations to optimize pressure distribution and stiffness during flange design.

3. General design considerations

3.1. General guidelines

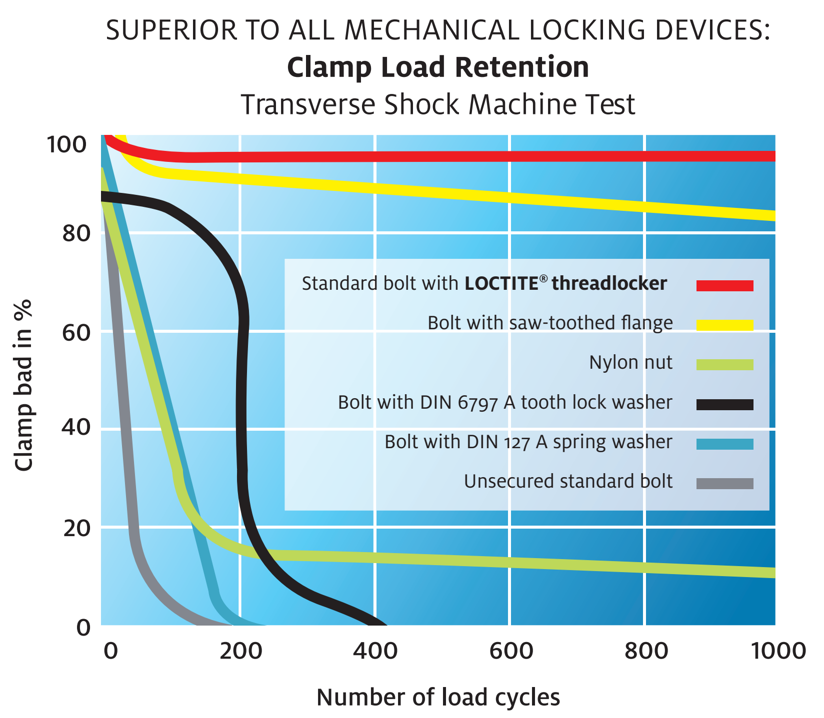
For the design of highly stressed gasketed joints, the following basic rules should be adopted:

- **Flange pressure distribution**
  It is necessary to achieve uniform flange pressure distribution within the permissible limits – which include the critical minimum sealing stress of the gasket and the admissible compressive strength of the flange material and the gasket.
- **Operating load of the gasketed joint**
  The gasketed joint has to be as rigid as possible in order to minimize deformations and relative movements.

While following the above-mentioned requirements, it is essential to follow the rules explained below for the design of joints independent of the sealing material:

- **Rigidity of sealing flanges**
  The rigidity of the sealing flange is indicated by the pressure distribution in the seal joint. The level of flange rigidity needs to be adequate so that the critical sealing pressure of the gasket is achieved in all flange areas.
- **Bolt preload**
  In order to minimize the loss of initial bolt load due to the relaxation of the gasket, it is necessary to ensure sufficient compliance of the flanges and the bolts (preload reserves). The loss of initial bolt load can be avoided or minimized by using LOCTITE® threadlocker, as shown in figure 2.

Figure 2: Loss of clamp load over time with and without LOCTITE® threadlocker.



- **Consider different thermal expansions**
  Due to different thermal expansions of aluminum housings with steel bolts, a cold environment can cause greater contraction of the aluminum flange and unload both the flange and the gasket. The minimum flange pressure required for a leak-free joint might then be compromised. High temperatures have the opposite effect, increasing the bolt and gasket load. In this case, the yield strength of the bolt and the compressive strength of the flange and the gasket are the limiting factors. Bolts and housings should have the same thermal expansion coefficient, if possible.
- **Stress and strain of the gasketed joint caused by external forces**
  In cases where the entire housing acts as a structure, the gasket joint should be as far as possible from the location where the forces feed into the housing.
- **Compressive stress distribution in the seal flanges**
  For optimum distribution of the bolt clamping load along the flange to the mid-point between the bolts, the bearing area of the bolt head should be as far away from the sealing area as possible. If the sealing area is in the middle of the effective bolt length (see figure 7), the adjusting compressive stress distribution in the housing is optimized. The theoretical straight connection lines between bolts (see figure 4 and 5) should not deviate significantly from the centerline of the gasket to allow a uniform compressive stress distribution within the whole flange width.
- **Adjusting the flange width to the compressive stress distribution**
  The bearing surface of the joint should be enlarged in the area of the bolt and reduced at mid-point between the bolts in order to obtain a more uniform compressive stress distribution in the seal joint.

3.2. Basic housing design

To develop a suitable sealing concept for the housing, the following rules are recommended for basic design:

- Create small, spherical housing openings
- Use same materials for the seal flanges
- Try to achieve uniform temperature distribution

3.3. Flange rigidity

The operational safety of a gasketed joint can be strongly influenced by varying the flange rigidity. The compressive stress distribution in the seal gap and in the flange between bolt head and seal gap indicates the rigidity of the joint.

Figure 3 shows three possible variations of flange design and their influence on the component rigidity.

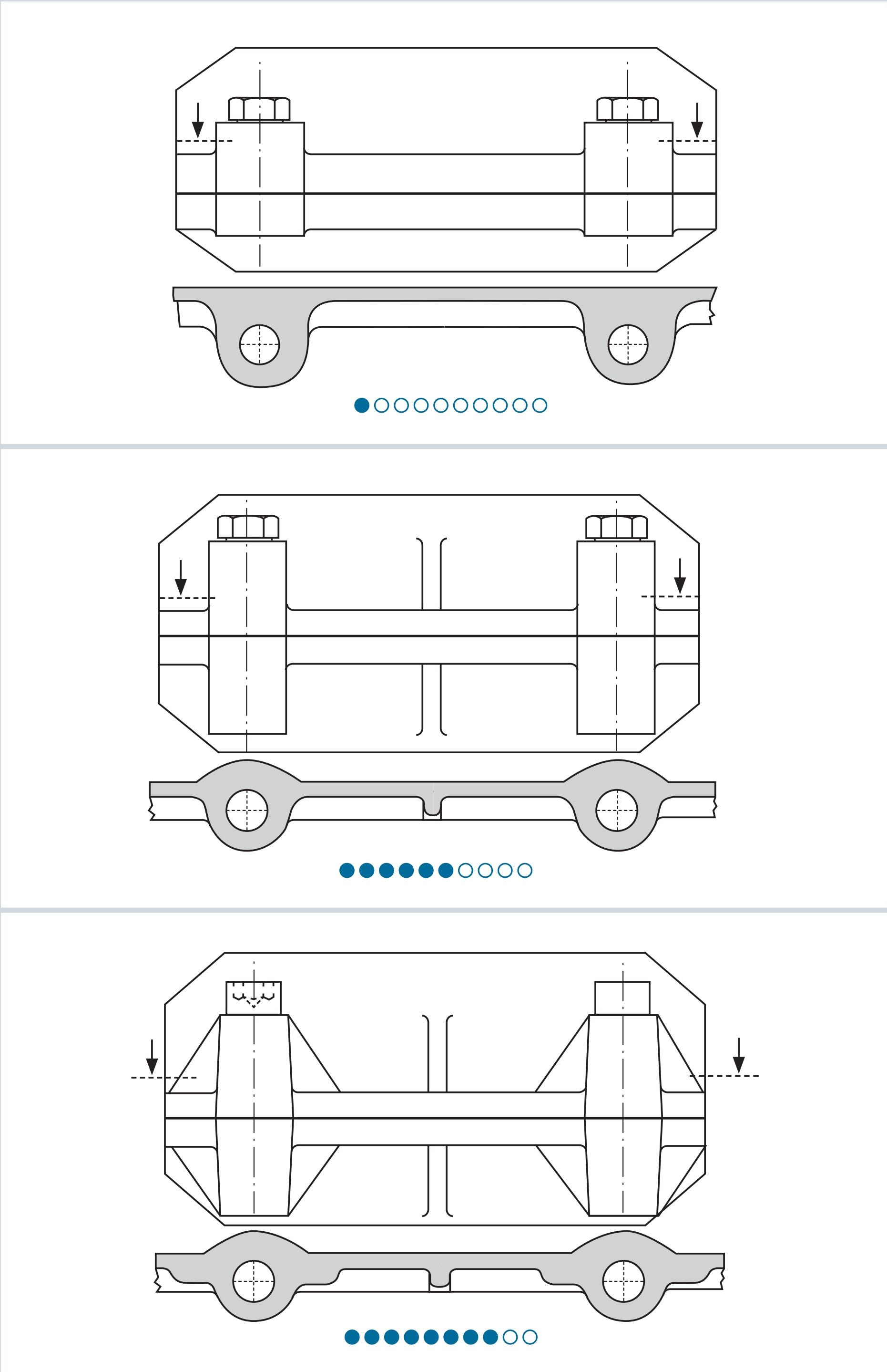
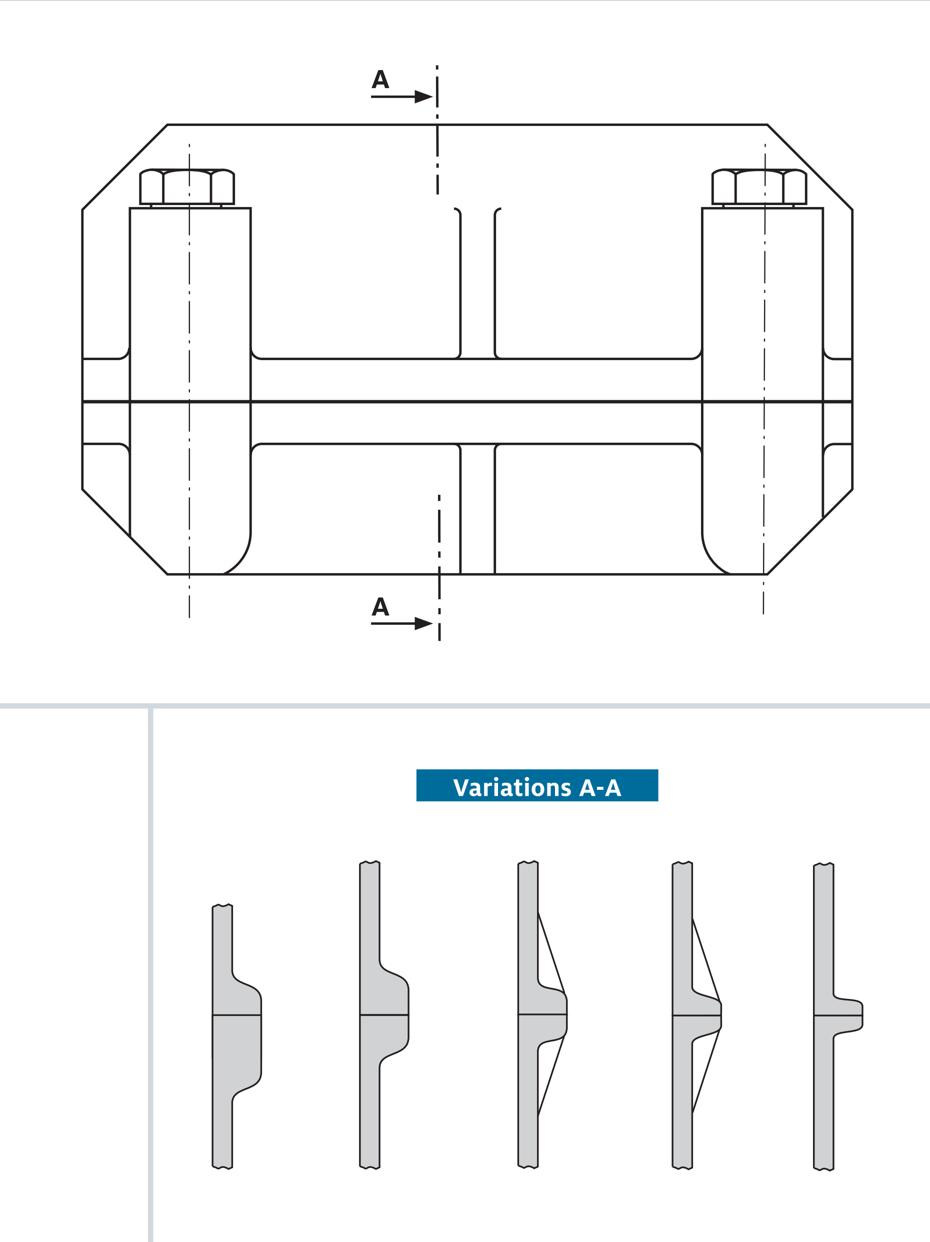


Figure 3: Evaluation of the flange design in regard to the compressive stress distribution (qualitative), stiffening of ribs and bosses at bolt location. The bottom illustration shows the best solution[1].

As flange rigidity decreases, the more complicated it will be to obtain the required minimum surface pressure at midpoint between two bolts.

Figure 4 is based on external research work[1] and illustrates the influence of flange rigidity on the use of static gasket types. Soft gasket material and non-curing liquid gaskets are only suitable for flanges with adequate bending rigidity.



Rigidity	●●●●●○	●●●○○○	●●●○○○	●●○○○○	●○○○○○
Light-Weight	●○○○○○	●●○○○○	●●●○○○	●●●●○○	●●●●●○
Preferred Range of Application	Soft Gasket Material (precut), CIP; Non-Curing Liquid Gasket (solvent-based)		Anaerobic FIPG; Embossed SLS or MLS		Silicone FIPG

Figure 4: Influence of flange rigidity on the use of static gasket types demonstrated on cast parts.

3.4. Bolt positioning and spacing

The best clamping pattern is invariably a combination of the maximum practical number of bolts, even spacing and optimum positioning.

Straight lines drawn from bolt to bolt, called bolt force lines, should be as close to the centerline of the gasket as possible to achieve uniform flange pressure distribution and avoid separation of the flanges due to potential prying (see figure 5).

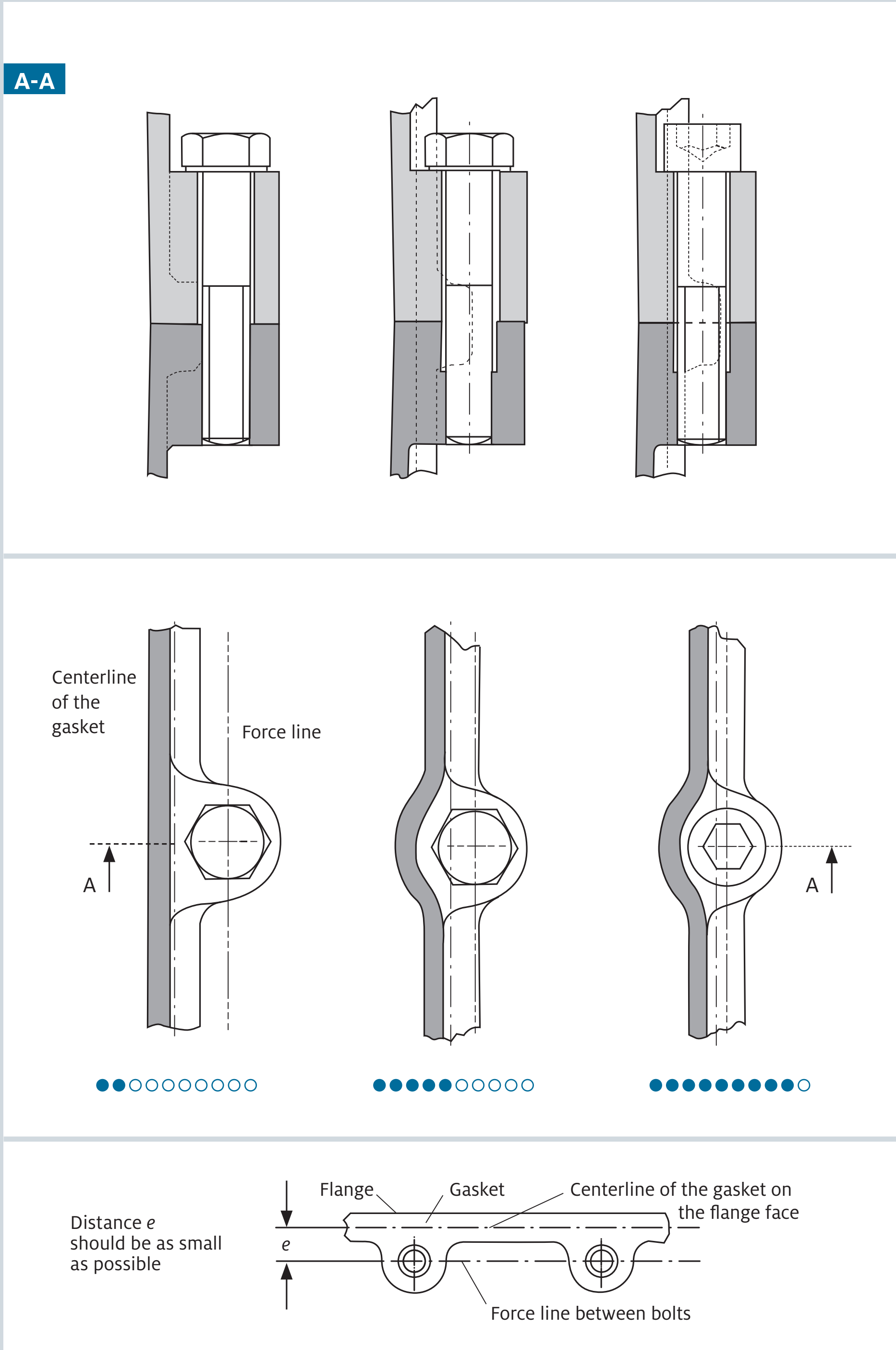


Figure 5: Evaluation of the distance between bolt force lines and centerline of the gasket in regard to the compressive stress distribution in the seal gap[1].

In addition, the position of the bolts is very important for the design of flange corner locations. Figure 6 shows different design variations and their valuation.

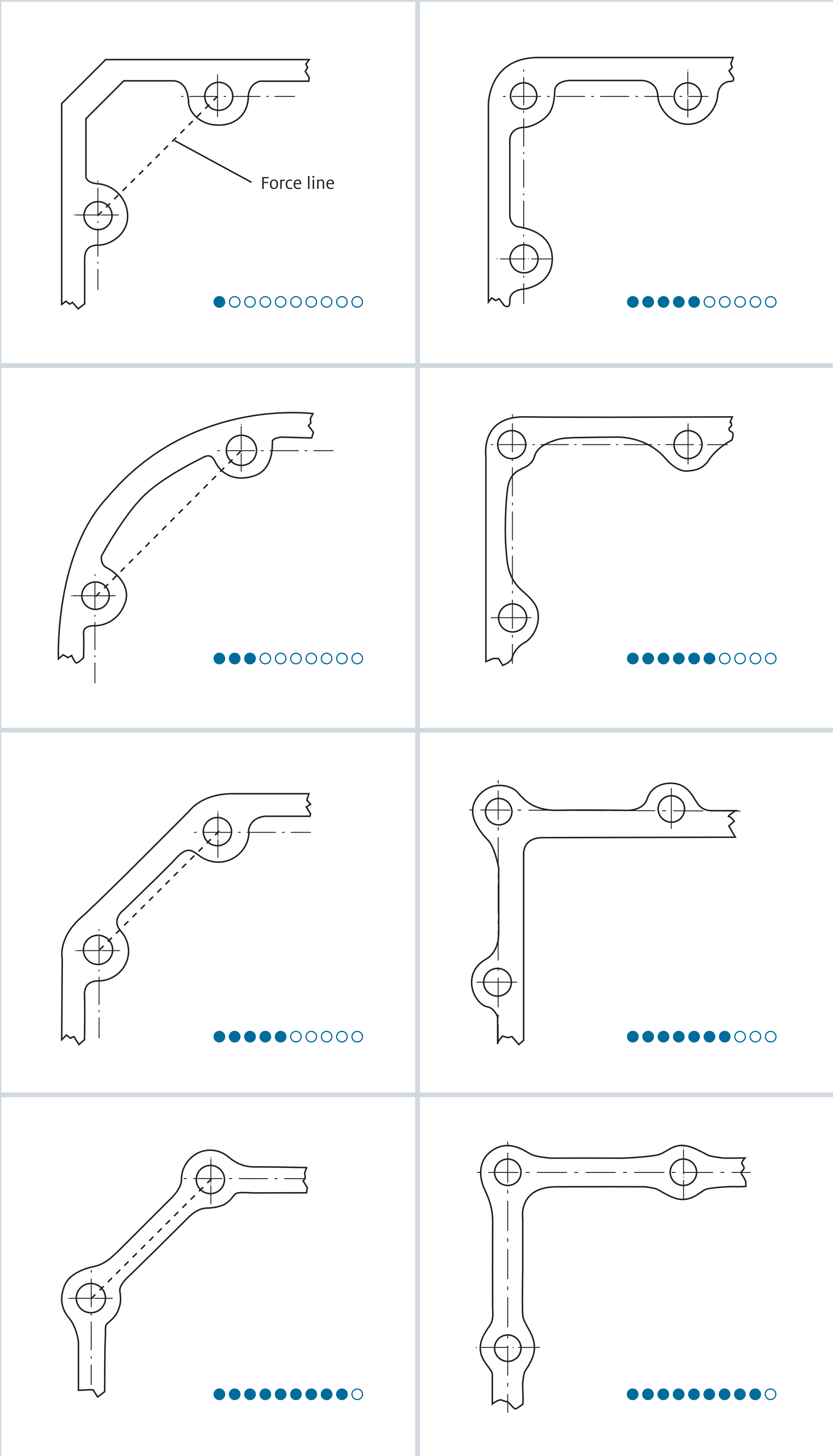
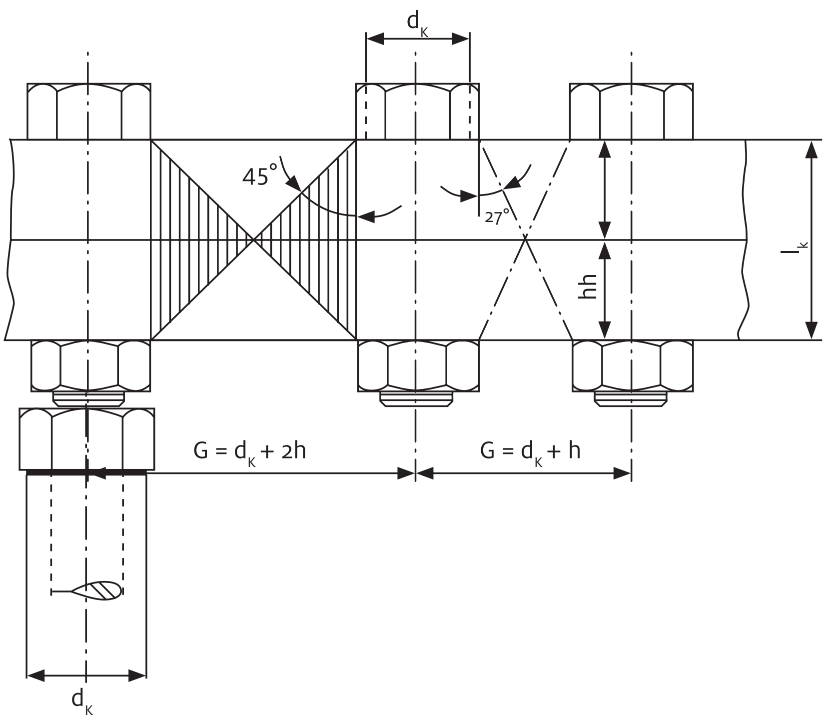


Figure 6: Evaluation of the position of the force lines to the centerline of the gasket in relation to the compressive stress distribution[1].

Theoretically, the bolt spacing can be calculated using the idealized model proposed by Rötscher. Rötscher's model says that the compressive stress in the flange between bolt head and seal gap is distributed as a cone with a half angular aperture of 45°, as shown in figure 7. For optimum bolt spacing, the pressure cones should at least touch each other or preferably overlap as demonstrated with the half-angular aperture of 27°. Rötscher's model recommends overlapping cones for bolted joints without gaskets. For gasketed joints, research projects[1] have shown that touching cones with a half angular aperture of 45° or greater are useful for the calculation of bolt spacing. For highly stressed gasketed joints, bolt spacing between the two limits 27° and 45° is recommended.

Figure 7: Pressure cone according to Rötscher.



$d_k + h \leq G \leq d_k + 2h$

d_k … Diameter of the bearing area of the bolt head

The equation shows that the flange rigidity as well as the effective bolt length are important parameters for bolt spacing. Figure 8 shows the resulting compressive stress distribution in the joint with variations of these parameters.

3.5. Bolt grade and length

- Select a bolt that requires 80% of the proof load as initial load.
- Select a bolt with an initial bolt load of roughly 3 to 3.5 times the normal operating tensile loads that can be applied (internal pressure, temperature effects, and external loads).
- Rule of thumb – when the length of the bolt is five times greater than the diameter, it can be elongated sufficiently to work as a spring between two flanges and dampen vibration.
- Optimum thread engagement length for steel is 1.2 times the diameter of the bolt; for cast iron, it is 1.5 times; for aluminum, it is 1.6 times plus the tolerance for the run out of the thread, for dynamic loading plus 20%.

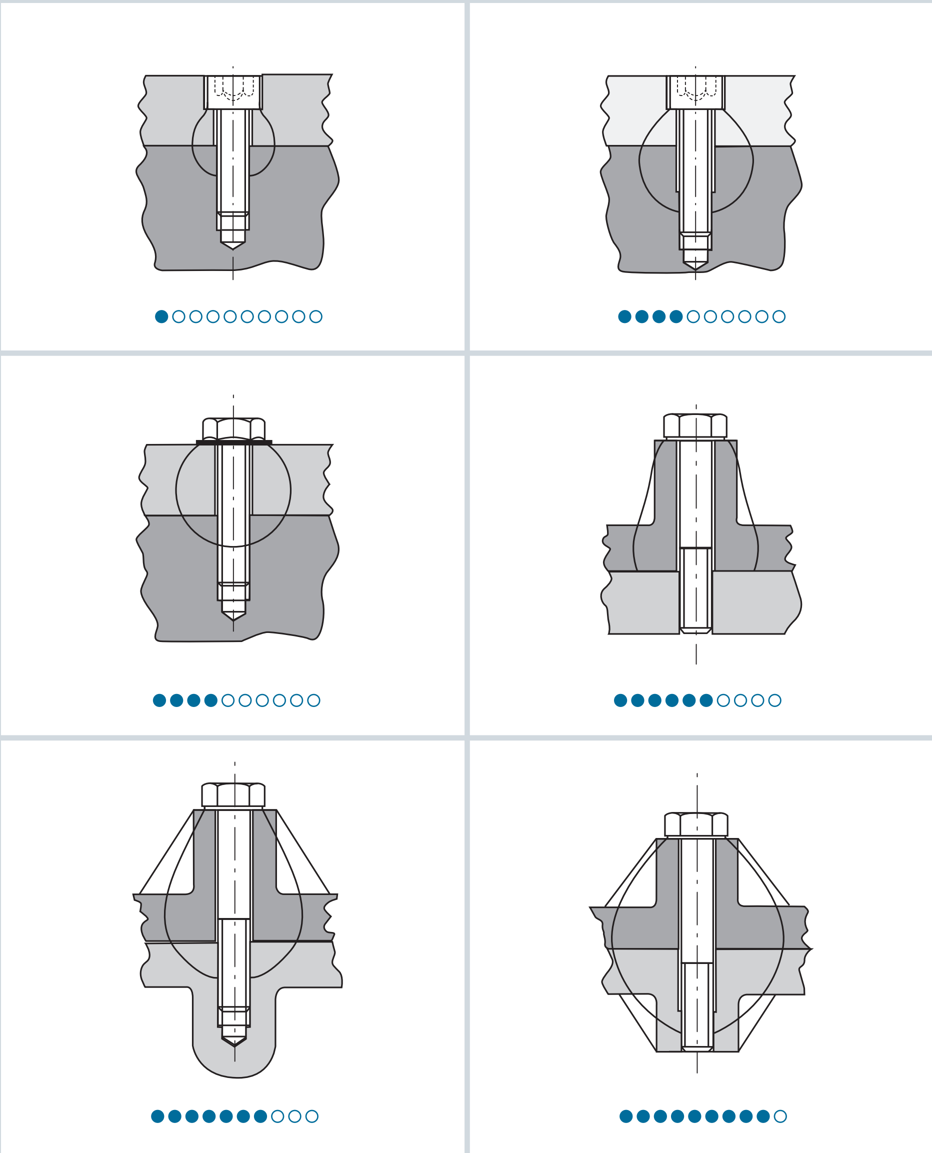


Figure 8: Influence of the flange design on the compressive stress distribution of the flanges.

3.6. Flange design verification

One of the basic rules for the design of highly stressed gasketed joints is to achieve a uniform flange pressure distribution within the gasket-specific permissible limits. It is necessary to know in the early stages of the design process if the required flange pressure is achieved in the seal gap.

The flange pressure distribution can be evaluated in a very early state with a Finite Element Analysis (FEA) or later on prototypes using a pressure-sensitive film, manufactured by Fuji Photo Film Company. A completely new design will rely on both systems since the FEA allows the design optimization in a cost-effective way and the imprint of the pressure sensitive film is needed for the confirmation of the numerical calculation.

To evaluate the stress distribution, the film is pre-cut to the shape of the mating flanges and holes are pre-punched for the fasteners. The film is then placed between the flanges and the bolts tightened to the specified torque. When pressure is applied, microcapsules break and a color-forming material is released. The microcapsules are adjusted to break at different pressure levels; therefore, the resulting color density is dependent on the amount of pressure. Thick red color indicates the applied pressure is high while fainter shades indicate the applied pressure is low (see figure 9). Using a commercially available Fuji densitometer, impression color density can be directly converted to stress readings.

A disadvantage of the system is that only the maximum applied force is recorded whereas the unloading of the gasket under operating conditions such as temperature, pressure or dynamic loads cannot be measured. These effects have to be evaluated by FEA. The film gives an indication of the weak points in gasketed joints, such as areas with low or no flange pressure so FEA can focus on these points for optimization. The film also shows machining marks and problems with flange mating tolerances, such as flatness and overlapping.

Besides the FEA, real-time flange pressure mapping is possible with the Tekscan thin-film pressure profile measurement system at the prototype stage. A high-resolution, matrix-based tactile sensor is placed between the flanges. The software supplied with the sensor is capable of dynamic data collection and displays where pressure cycling or the recording of an event might be important.

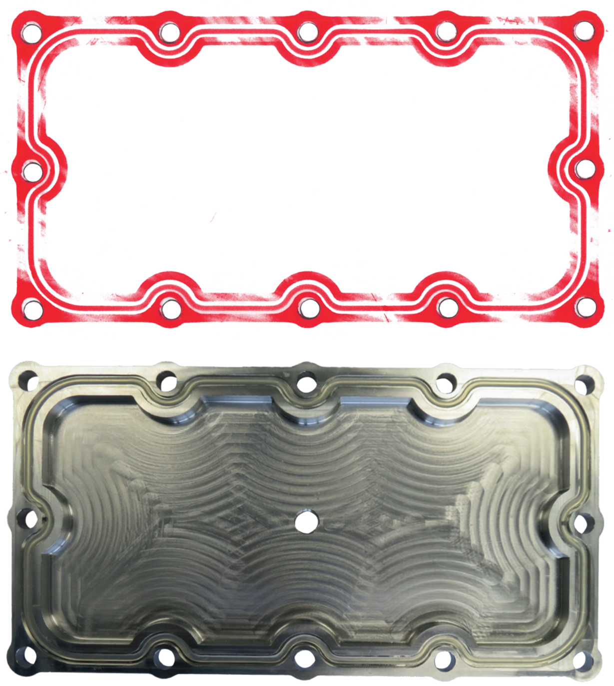


Figure 9: Image of a test flange with a CIPG dispensed onto it and the corresponding Fuji Test. It is possible to notice that despite flange imperfections and irregular flange pressing, the sealing force of the gasket is relatively uniform and sufficient to keep the system tight.

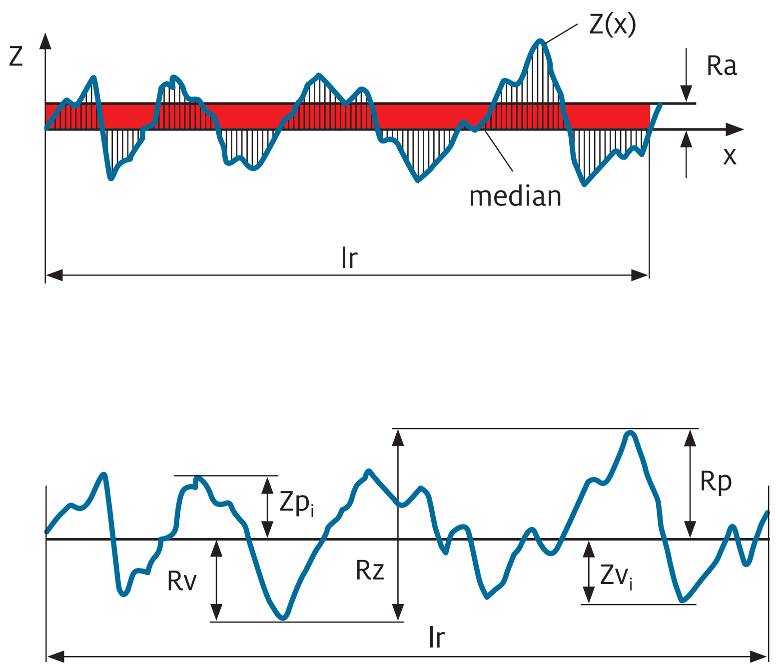
3.7. Surface finish

Surface finish or surface texture are terms used to describe the general quality of a workpiece surface. Surface finish consists of roughness, waviness, lay and flaws. Bearing and locating surfaces usually require close dimensional and surface finish control for proper functioning.

The surface finish is very important for compression gaskets, since the initial compressive load required to deform the gasket into the flange surface irregularities increases with rougher surface finish. Moreover, surfaces with a too rough finishing may have percolation channels because the gasket cannot be deformed to fill all existing gaps in the surface. In these cases, these channels will create a leakage path through the assembly joint. On the other hand, if the flanges have a too smooth surface finish, there will not be the necessary friction between the mating surfaces to fill the gaps, which is necessary to keep the right contact position and avoid potential leakage. In extreme cases, with a very smooth flange, there will be reduced friction restraining the gasket from extruding under the influence of the internal pressure.

Surface finishing has also very high impact on the surface cleanliness prior to sealing, since flange contamination becomes more difficult to remove from rough surfaces.

The surface characteristics are determined primarily by means of a profilometer according to DIN EN ISO 4287. The two most common measurements of surface finish are Ra and Rz, as shown in figure 10.



$$Ra = \frac{1}{lr}\int_{0}^{lr} |Z(x)|\,dx$$

Figure 10: Ra and Rz according to DIN EN ISO 4287.

Ra is the mean value of the absolute values for the profile deviations within one individual measurement section lr.
Rz is the maximum peak-to-valley height within one individual measurement section lr.

Previously, Rz was obtained from the mean value of the absolute values of the heights of the five highest peaks and of the five deepest valleys for five individual measurement sections within the evaluation length (Rz ≥ ten-point height Rz).

The Ra value alone is not sufficient to determine roughness, since different surface textures can have the same Ra value, as shown in figure 11. At least Ra and Rz should be measured, but using Ra, Rz, Rmax and Wt provides a more accurate picture.

Maximum peak-to-valley height Rmax is the greatest individual peak-to-valley height of the entire measurement section ln = 5 x lr.

Wt is the maximum profile height of the filtered waviness profile within the entire measurement section ln.

While it is not possible to stipulate maximum and minimum values for surface roughness, since the gasket performance is also dependent on other factors, such as operational temperature, internal pressure and flange design, it is important to avoid the extremes of surface finishing when working with compression gaskets.

A typical recommendation of surface finishing for CIPG is Ra 3.2–12.5 µm, Rz < 35 µm and Rmax < 50 µm. Moreover, the sealing surface must be free of nicks, burrs or scratches.

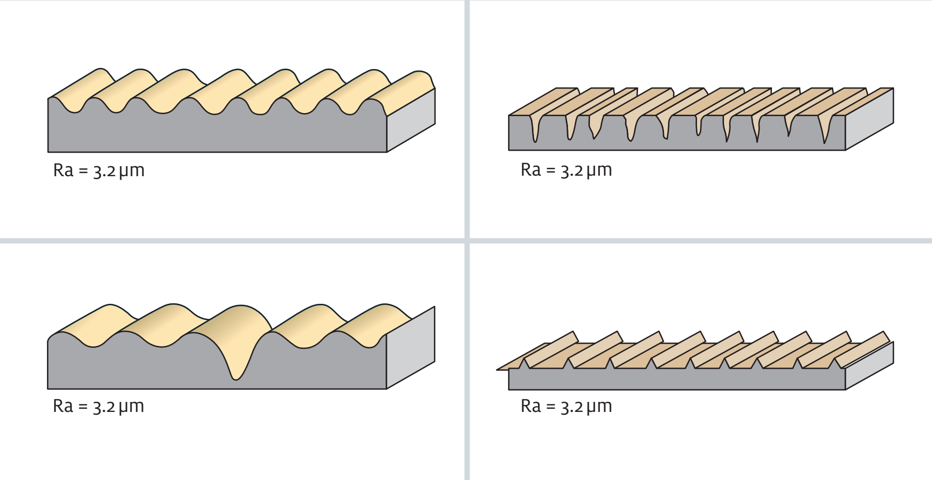


Figure 11: Different profiles with the same Ra values.

4. CIPG application areas and advantages over solid gaskets

Unlike conventional elastomeric gaskets, CIPG technology enables higher design flexibility, since different sealing designs can be saved in the equipment memory.

The main benefits of CIP over SGMs are:

- **Increased productivity**
  CIP sealants can be applied by fully automated robotic dispensing or screen printing systems.
- **Reduced tooling costs**
  High investments in tools and their maintenance are not required. Single investment in dispensing and curing equipment with no/very limited additional costs required.
- **Supply chain simplification**
  No need for a SGM supplier. CIPG can be dispensed directly at the production line, at the component supplier or sub-supplier.
- **Easier handling of vertical components**
  CIP sealants can be applied to both horizontal and vertical assembled flange faces, as they adhere to their substrate. Unlike solid gaskets, they do not require additional adhesive to maintain their position on vertical flange faces.
- **Reduced inventory costs**
  CIP sealants can seal different flange geometries, unlike solid gaskets that require stocking many different gaskets to fit the different geometries.
- **Design flexibility paths**
  CIPG dispensing path can be easily adjusted to design modifications and new parts.
- **Chemical compatibility**
  Polyacrylate-based CIP sealants demonstrate excellent resistance to powertrain lubricants (automatic transmission fluids – ATF, engine oil and gearbox oil) as well as to corrosive environmental conditions (for instance, salt spray).

4.1. Polyacrylate-based CIP gaskets

Polyacrylate-based CIP products cure when exposed to UV radiation at room temperature and have excellent lubricant resistance, even when subjected to high temperatures. These products are best suited to seal powertrain applications under the hood where flanges have moderate flexibility.

Due to their improved compression range and high temperature resistance, these products also show excellent performance sealing covers against environmental fluids and corrosive saltwater environment.

Recommended applications are shown in figure 12 and include intake manifolds, oil pans, grommets, cylinder head covers, front covers, oil filters, valve covers, battery packs, oil pumps, electronic control units (ECUs), inverters and converters.

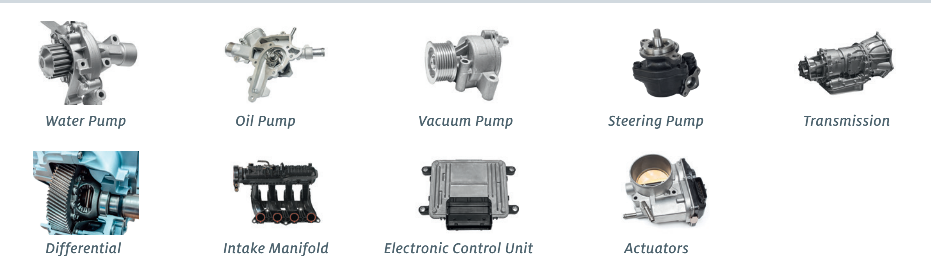


Figure 12: Typical applications of Polyacrylate CIP Gaskets.

5. Design recommendations for CIP gaskets

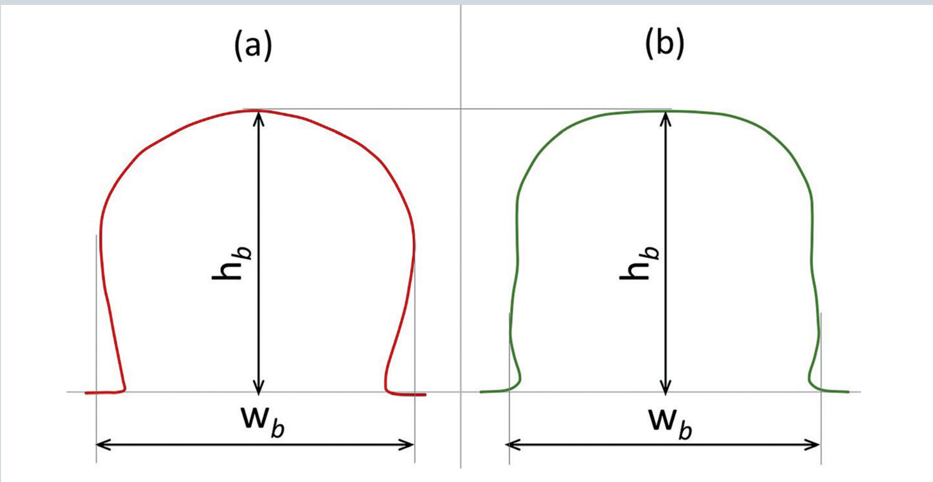
5.1. Gasket bead design

The height of the bead as formed after dispensing and UV curing and its aspect ratio, defined as the initial height h_b to (total) width w_b ratio (figure 13), are the shape parameters corresponding to the ability of the gasket to capture a wide range of compression levels and tolerances derived from the parts to be sealed. The shape of the gasket bead is driven by several parameters, among them:

- the nozzle orifice (for a circular tip, diameter and deviation from the vertical),
- the nozzle tip distance to the substrate,
- the robot speed,
- the throughput rate and
- the material rheology

The current dispensing machines and processes are capable of achieving aspect ratios varying from 0.6 to 0.9. The single bead cross-sectional shape is assumed to be semi-elliptic but may deviate with increasing aspect ratio. The bead exhibits an undercut with a portion of the total width adhering to the substrate (figure 13a). However, for single bead dispensing, high aspect ratios are achieved at the expense of dispensing speed. In other words, the higher the aspect ratio, the slower the process. This may not affect small bead designs and low-volume production, but it is not desired for high production volumes. To achieve high aspect ratios within an adequate production cycle time, a second design or dispensing method called bead-on-bead is recommended (figure 13b). It involves dispensing two beads with moderate aspect ratio on top of each other before curing, at high dispensing speeds. In this variation, the final cross-section design is also stable through the profile, achieving the same sealing reliability as a single bead.

Figure 13: Gasket bead cross-section geometry after curing: (a) single bead, (b) bead-on-bead.



Design rules and recommendations address the issues of purposeful compression and space needed for a groove or step to house the bead and provide adequate void volume for the flow of the material in compression. They are based upon functional experiments, material testing, and numerical analysis results.

5.1.1. Minimum required compression

The gasket minimum compression corresponds to the minimum sealing pressure (figure 14) along the contact width of the compressed bead required to keep the system tight.

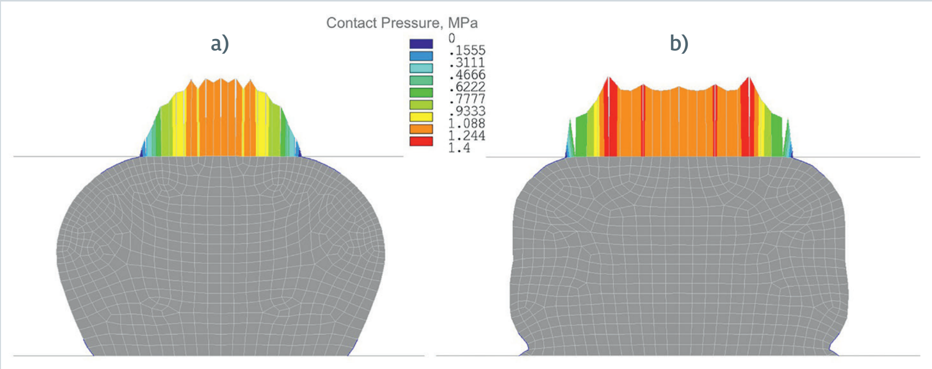


Figure 14: Contact pressure along the contact line: a) single-bead and b) bead-on-bead gasket at 15% compression.

The contact pressure depends on the compression level and, to some degree, on the aspect ratio of the bead. At lower compression levels, single beads with high aspect ratio provide slightly greater maximum contact pressure than gasket profiles with low aspect ratio (figure 15a). This can be explained by the smaller profile curvature affecting the contact conditions at the initial contact stage. By increasing the compression, the contact pressure becomes greater for the low aspect ratio beads, because they are wider and generate higher resistance to compression at intermediate to long-term contact stages.

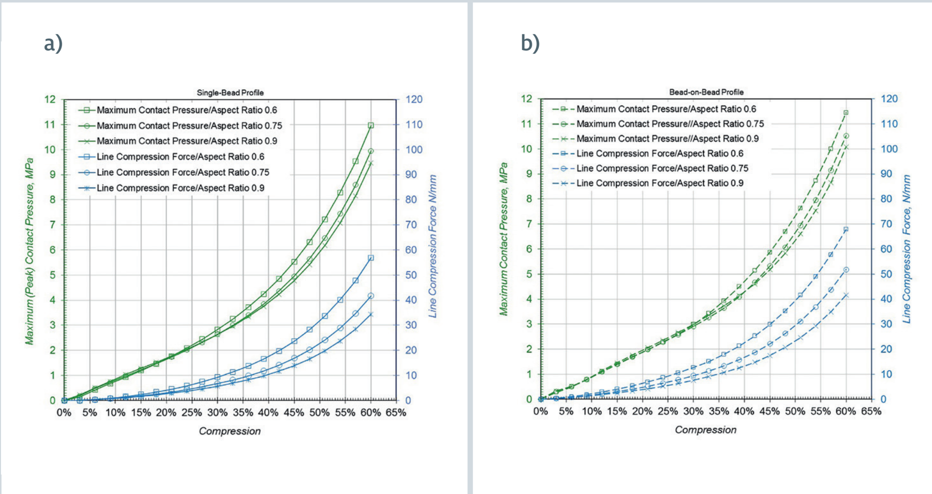
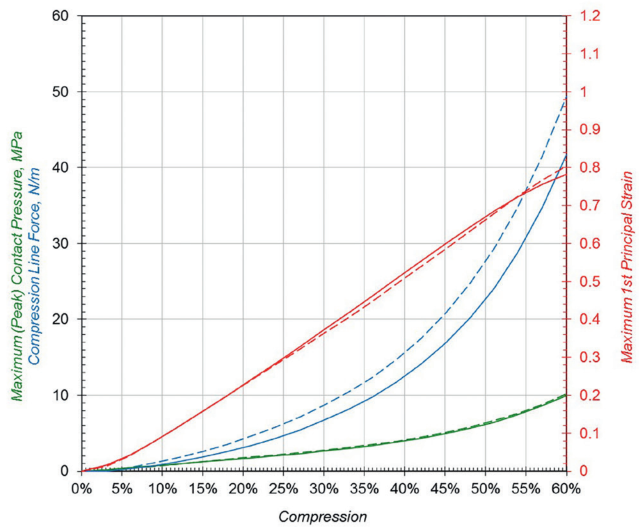


Figure 15: Contact pressure depending on compression and aspect ratio: a) single-bead gasket b) bead-on-bead

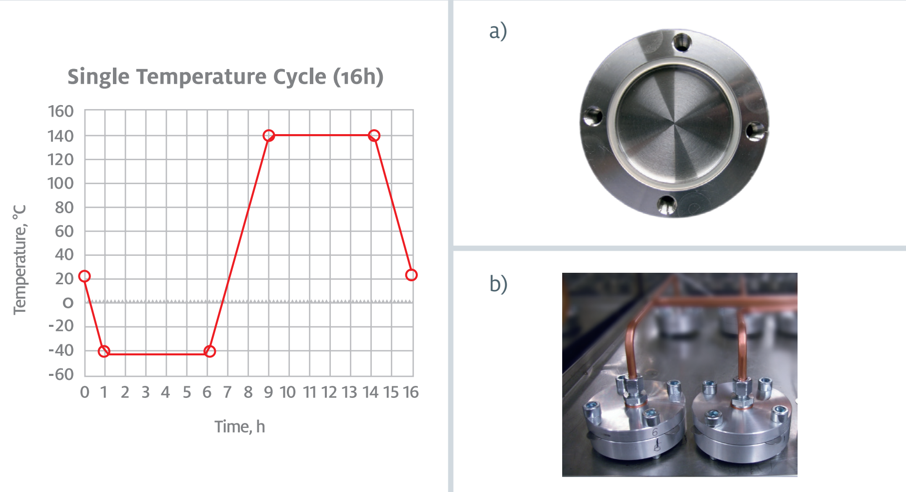
The bead-on-bead design provides slightly higher maximum contact pressure compared to the single-bead design. However, the compression line force increases significantly, impacting the force required to assemble the flanges. As the sealability can be associated with the contact pressure and its integral along the contact width, the bead-on-bead design has therefore a higher sealing performance (figure 16).

Figure 16: Comparison between single-bead (solid lines) and bead-on-bead gasket design (doted lines) with an aspect ratio of 0,75.



The minimum compression level for retaining sealability is 15% for both single and bead-on-bead designs. This value was validated by testing gaskets immersed into oil under thermal cyclic loading conditions (figure 17).

Figure 17: Thermal cyclic test conditions (800h), test assembly: (a) flange with sealant bead dispensed onto, (b) test assembly with cover plate and pressurized air valve.



For practical applications, the effect of the aspect ratio on the sealing pressure may considered to be negligible, since the contact pressure does not vary distinguishably with the aspect ratio for the minimum compression of 15% required for sealability.

5.1.2. Maximum allowed compression

The maximum compression allowed for a typical sealant bead has been determined by the failure of a standard gasket profile immersed in oil at 150°C for 1,000 hours.

Numerical analysis by the finite-element-method has confirmed that failure occurs when the corresponding material strain limit is exceeded, as shown in red in figure 18. The strain limit has also been evaluated in compression testing of cylindrical plugs subjected to identical temperature and medium conditions.

In practical application testing, failure occurred at the edges of the upper contact surface, directly above the material high straining area identified at the central part of the bead. The strain peaks at the lower profile edges where the bead adheres to the substrate, indicated by the numerical analysis, are local and can be attributed to the profile idealization, used for analysis purposes. In reality, the material relaxes after slight loss of adhesion or limited plastic deformation.

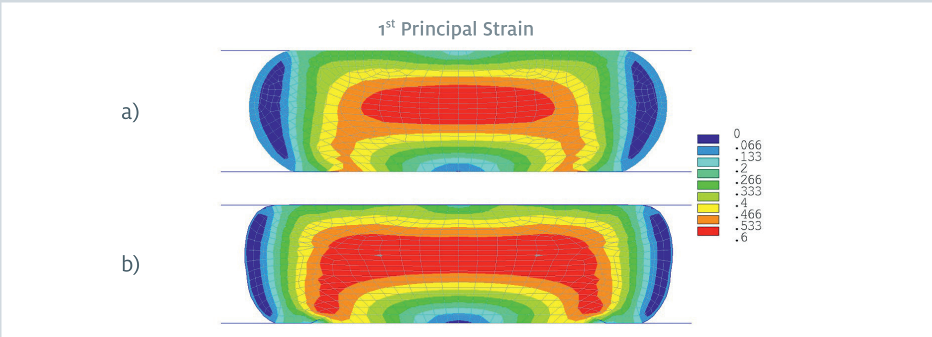


Figure 18: Strain relief after compression at 45%: a) single-bead gasket; b) bead-on-bead gasket.

The material straining results considered both compression, thermal expansion and volume change due to swelling. Immersion in ASTM SF105 (engine oil) resulted in maximum volumetric swelling (worst case), while immersion into other oils led to significantly lower volume increase (<10%). Figure 19 shows that for a bead profile experiencing volumetric swelling equal to 17%, the strain limit is achieved at compression levels above 45%.

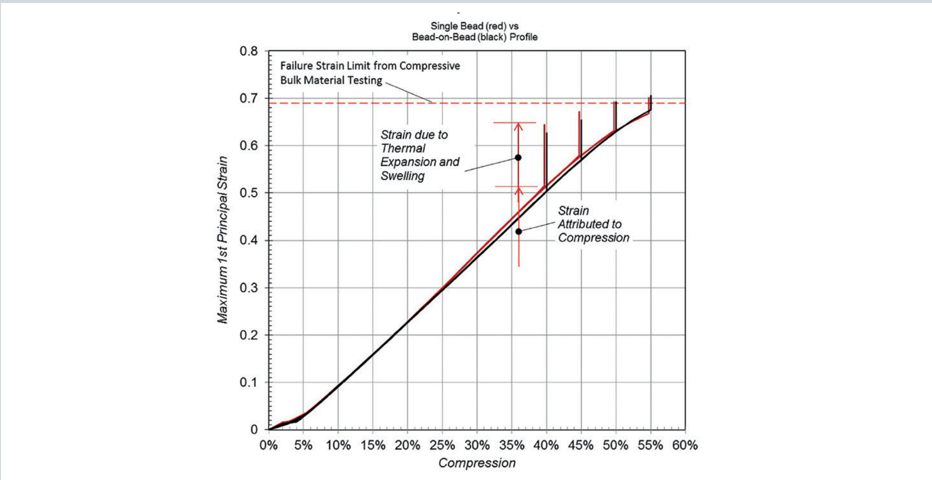


Figure 19: Compression-strain curves for bead profiles at different compression levels for both single bead and bead-on-bead, shown in red and black, respectively. The total strain resulting of compression and thermal expansion/swelling exceeds the failure limit of the material, leading to failure at compression level above 45%.

As there are no significant behavioral and performance differences between single bead and bead-on-bead designs, the next sessions of our design guidelines for CIP gaskets will apply the term bead when referring to the gasket.

5.2. Flange design

For simplification reasons, the flange design recommendation is the same for both single bead and bead-on-bead designs. The figures will illustrate just single bead design.

5.2.1. Groove design

A void-volume design requires a properly sized groove to house the bead and provide adequate void volume for the flow of the material being compressed. The general underlying assumption for Cured-In-Place Gaskets is that the bead shall fill 60% to 75% of the groove volume approximately to avoid excessive load conditions after compression and to accommodate swelling and thermal expansion effects (figure 20).

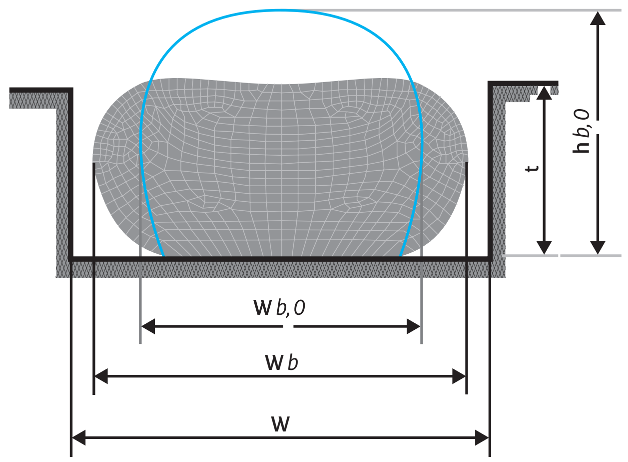


Figure 20: Groove design.

Based upon numerical simulations, the expected width of the bead under assembly conditions, w_b, may be estimated with significant accuracy. Its value corresponds to a minimum required groove width, which has to be appropriately enlarged by a safety factor for design purposes. The estimated width takes into account both deformation due to compression after assembly and expansion due to thermal loading and swelling (figure 21).

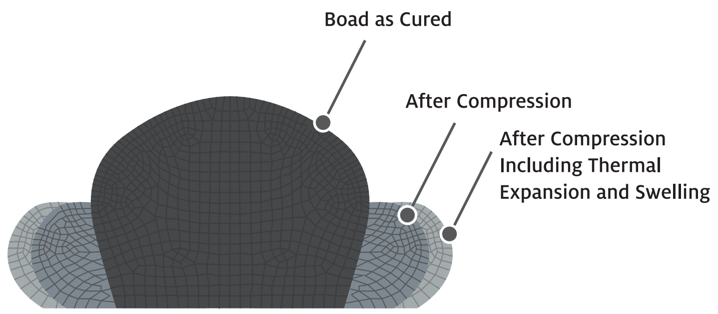


Figure 21: Bead deformed by compression and subsequent thermal loading and swelling in engine oil environment.

Beads with a higher aspect ratio usually require smaller groove width values. Figure 22 illustrates the required space for two different aspect ratio values, depending on the bead height and the swelling index resulted from immersion in oil at 150°C. The chart considers a maximum compression of 45% and swelling range from 5 to 17%.

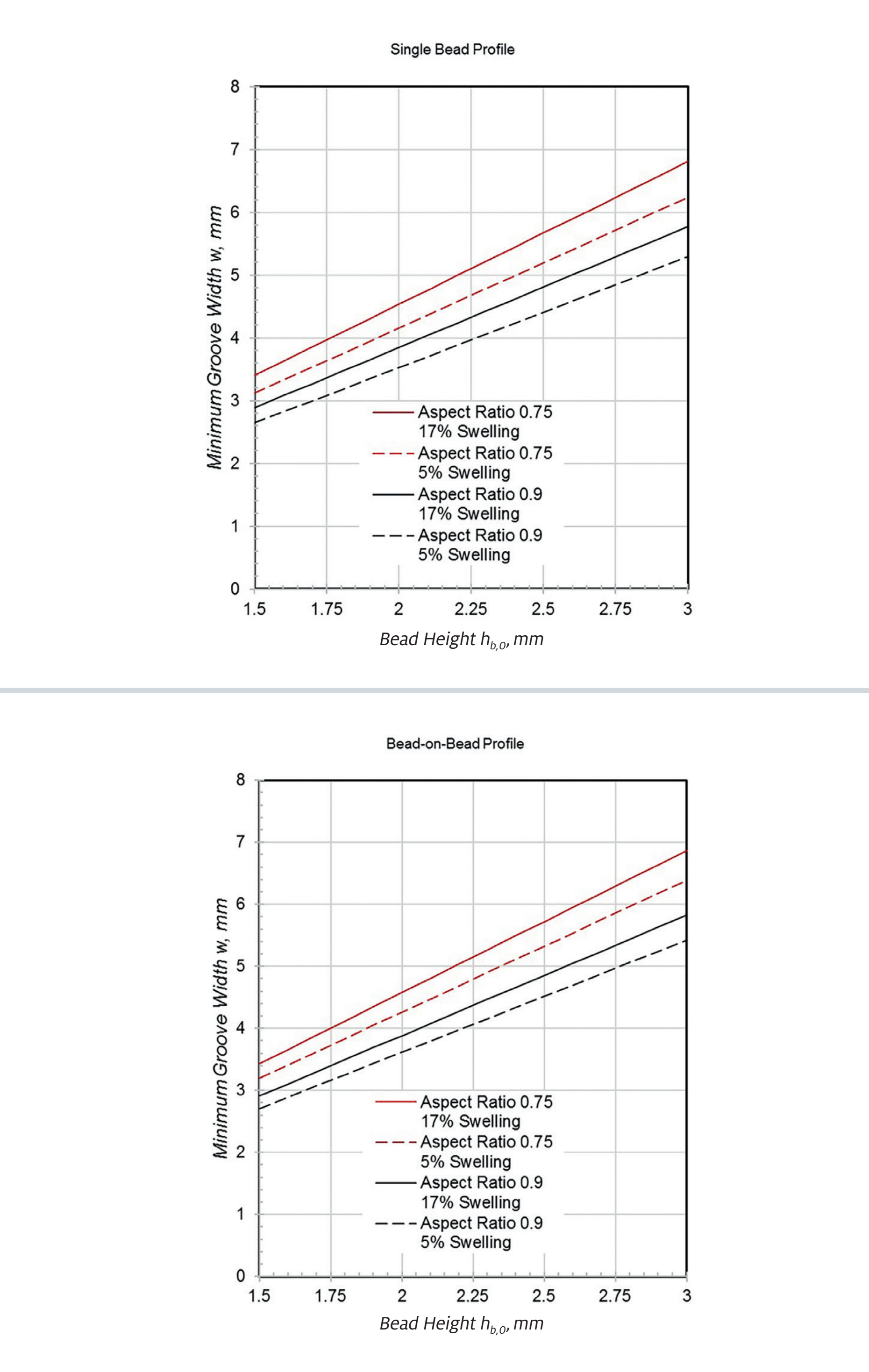


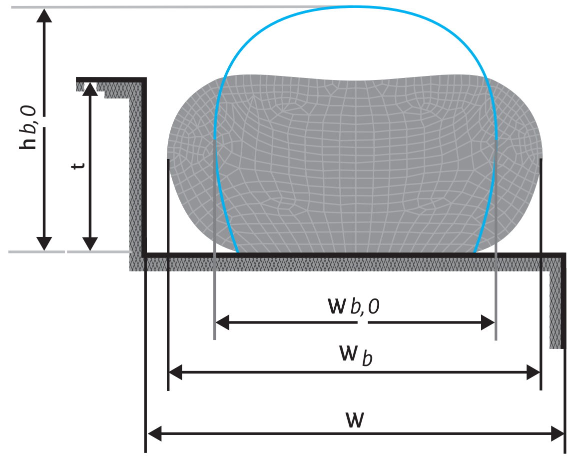
Figure 22: Minimum groove width corresponding to a bead deformed by 45% compression and immersed in oil at 150°C.

5.2.2. Step design

A step design uses an L-shaped cross section flange area to place the sealant bead. In practice, the sealant bead is housed in a one-sided groove, which is open to the operating medium.

A simplified design approach is to position the bead centered above the available step. In this case, the required step width corresponds to the groove width estimated for the groove design (figure 23).

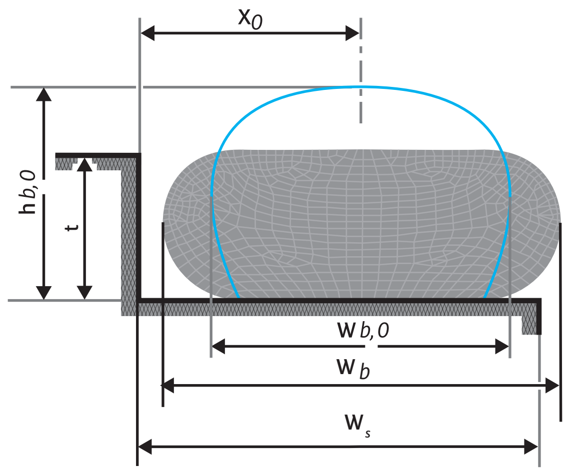
Figure 23: Step design: simplified approach.



However, the step design requires less flange area than the standard groove design, because the second groove wall can be omitted. In addition, the bead can be immediately positioned closer to the end of the flange (figure 24). The additional benefit derives from the fact that the bead, when properly positioned, is allowed to deform and overhang to some degree at the flange end. In this case, the centerline of the bead should be positioned in appropriate distance x_o to the remaining sidewall, which is equal to half the width required for the groove design.

$$x_o=0.5\bullet w$$

Figure 24: Step design: optimized flange area.



5.2.3. Tolerances

The best sealing performance is achieved when the surface profile tolerance of the step/groove is kept within 0,20 mm to the reference surface (figure 25). The mating surface should have a maximum flatness of 0,10 mm for each 100 mm or between neighboring bolts for best results.

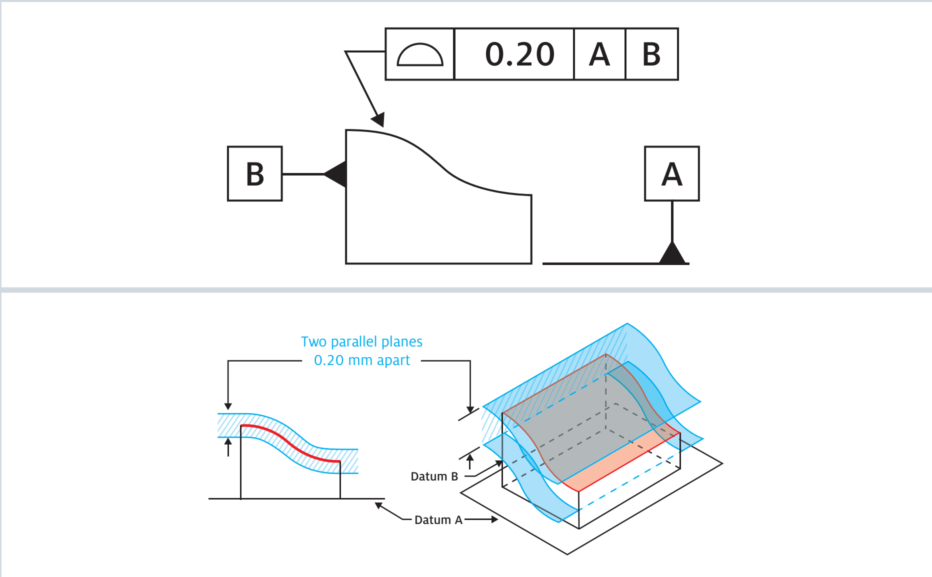


Figure 25: Profile of a surface.

The tolerances recommended above are merely a guidance that should result in an adequate compression window for CIP and enough sealing force. **We strongly recommend a stack-up analysis to define minimum and maximum gaps resulting from tolerance chains.**

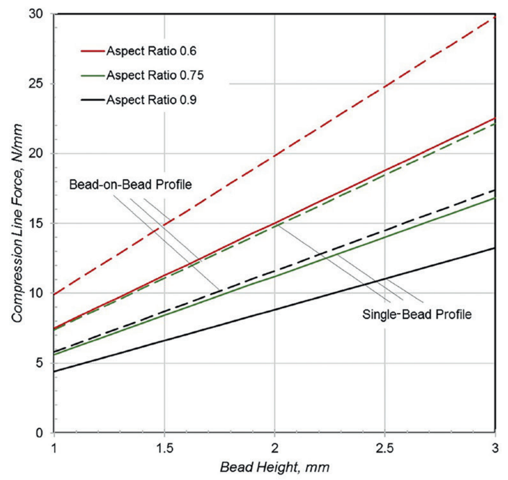
5.3. Assembly load

The load required to compress the sealant bead at a desired compression level depends on the effective seal length and is therefore expressed as force per bead length (line compression force). It depends on the bead height, its aspect ratio, and the compression level.

For a compression level of 45%, the assembly load can be estimated using the diagram in figure 26. The estimation is based upon numerical analysis using data from material testing and functional records. It assumes the assembly load to be applied at standard speed neglecting viscoelastic effects.

The line compression force can be used to estimate the size and number of fasteners needed for proper assembly. However, the underlying assumption is that the flange behaves ideally stiffer. In practice, provision should be made for ensuring uniform compression along the entire gasket area by appropriate part design and fixing patterns.

Figure 26: Compression force required for proper assembly at 45% compression for different aspect ratios.



5.4. Material parameters used to define design characteristics and simulation

5.4.1. Material response behavior

Henkel's polyacrylate-based sealant is a typical rubber-like material. Quintessential features of its stress-strain response are its nonlinearity, and its recoverability. It can undergo large elastic deformations in the order of >150%, and is considered to be practically incompressible because there is negligible volume change under applied stresses. This may be primarily attributed to the deformation mode related to straightening of molecular chains. Although the material response is isotropic, it exhibits on macroscopic level considerable stiffening in compression.

The mechanical behavior of rubber-like materials is rather entropy-driven than energy-driven elasticity, being the last one applied to usual crystalline solids and usually referred to as hyper-elasticity. The mathematical description of the stress-strain behavior makes use of the strain energy density function, W, which is some arbitrary function of the extension (stretch) ratios in the three principal directions, or of the strain invariants. Its derivative with respect to a particular strain component gives the corresponding stress component.

There are several distinct approaches of the strain energy density function available, most of them leading to polynomial expressions including higher-order terms. Common strain energy functions are among others Mooney-Rivlin, Ogden, and a general form of higher-order polynomials.

The use of higher-order models implies complications in determining the material coefficients. Simpler forms of the strain energy density function are of considerable interest. The neo-Hookean function represents the simplest form of strain energy potential, although it has an applicable strain range of up to 30% in tensile loading. A significant advantage is that a fit of the model to the stress-strain curve in one strain state is often adequate for predicting stress-strain curves in other strain states (unconditional stability).

Hyperelastic material constants are usually obtained through curve fitting of stress-strain data of one or several test modes. For sealing applications, the primary deformation mode is compression. One simplified way to evaluate the material behavior data is, therefore, to conduct uniaxial tensile testing followed by a simple compression test on cylindrical plugs for validation purposes, the latter as shown in figure 27. In order to minimize the frictional effects at the interfaces, the specimen ends are lubricated using silicone oil. The friction coefficient estimated by appropriate measurement is in the range of 0.05.

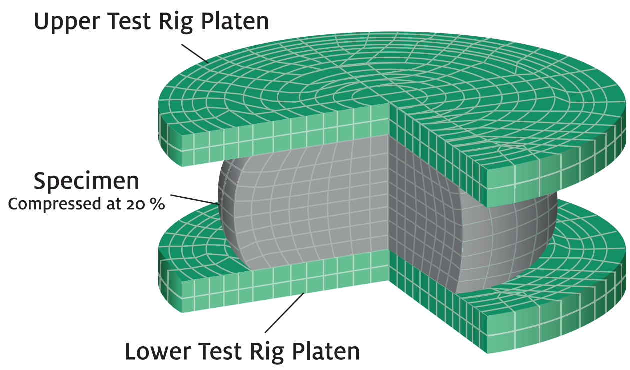


Figure 27: Simple compression test for validation purposes in ¾ axial representation.

Figure 28 illustrates the curve fit quality for suitable material options in both tensile (positive) stress-strain region and their prediction of the response of the simple compression specimen in comparison to the measured data in the negative (compressive) stress-strain region.

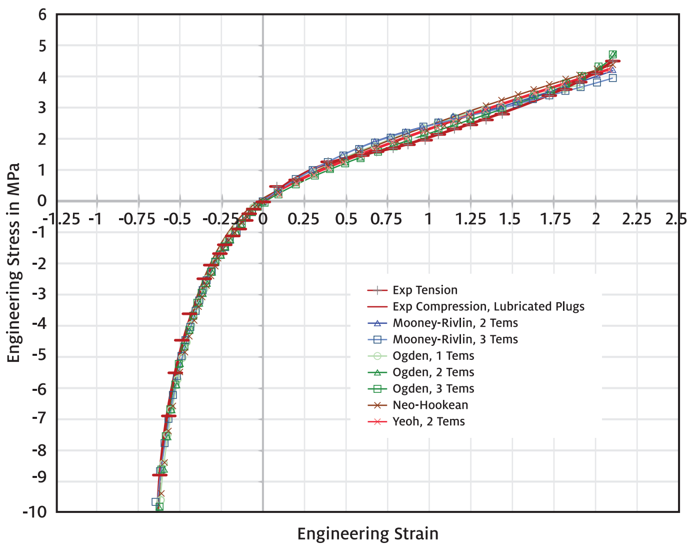


Figure 28: Comparison of hyper-elastic response prediction at 23°C and experimental data.

The choice of one particular hyper-elastic material option from those adequately fitting the test data has limited effect to the strain of a compressed sealant profile. In addition, the contact pressure curves under compression are virtually indistinguishable whatever hyperplastic material option is chosen up to a significant compression level. In general, low order material options are preferably used over higher-order models. For the purposes of numerical analysis for the present guideline, the 2-parameters Ogden material option has been applied as sufficiently accurate but with limited complexity of the used strain energy function.

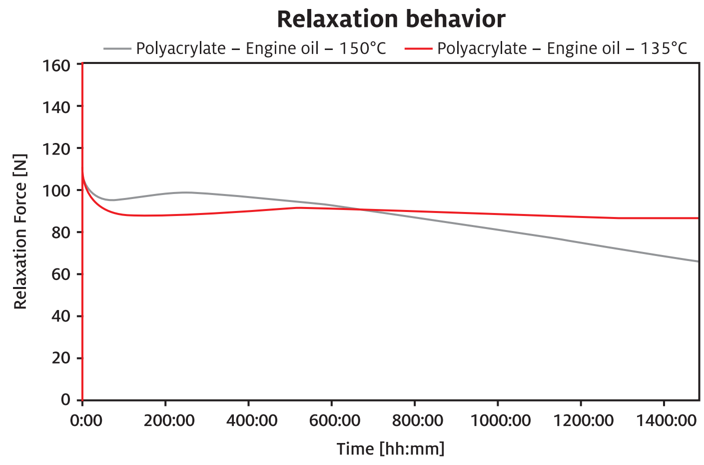
5.4.2. Material failure

No uniform criteria exist for predicting the rupture of rubber-like materials under arbitrary loading conditions. A widely used approach assumes failure to occur when the maximum principal strain achieves a critical value. The strain limit values applied can be estimated from tensile or compression testing. Tensile testing of bulk specimens for failure has instinctive appeal for engineers because of its simple and direct approach. However, bulk test specimens may fail prematurely if the specimen contains flaws or irregularities from manufacturing or die cutting. For purposes of the present guideline, the strain limit has been estimated based upon compression tests on cylindrical plugs with the contact surfaces being lubricated using silicone oil. The strain limit was then validated by numerical analysis of tested sealant profiles.

5.4.3. Stress relaxation behavior

Stress relaxation describes how the gasket material relieves stress under constant strain. The reduction of stress is evident by the gradual decrease of gasket contact pressure over time. Stress relaxation effects are more pronounced under thermal loading, as shown in figure 29.

Figure 29: Relaxation behaviour in engine oil at 135°C and 150°C: Temperature has a high influence on elastomer relaxation behaviour, noticeable by the downwards slope of the grey line (150°C) compared to an almost straight horizontal red line (135°C). The slight increase in force seen after 200h at higher temperature (grey line) happens due to elastomer faster swelling rate.



Compression set is the term, which describes the loss of elastic memory of the elastomer, the better the elastomeric memory the lower the compression set.

Compression set is generally determined in air or oil aging using a cylindrical rubber button of known thickness that is compressed to a fixed height at a defined temperature for a specified period of time. The button is then released, allowed to recover for a specified time and the thickness is measured at room temperature. Compression set is the height that is not recovered, expressed as a percentage of the amount by which it was compressed (figure 30). Zero percent (0%) indicates no relaxation has occurred whereas 100% indicates total relaxation, i.e. the seal only comes into contact with the mating surfaces but no longer exerts a force against those surfaces.

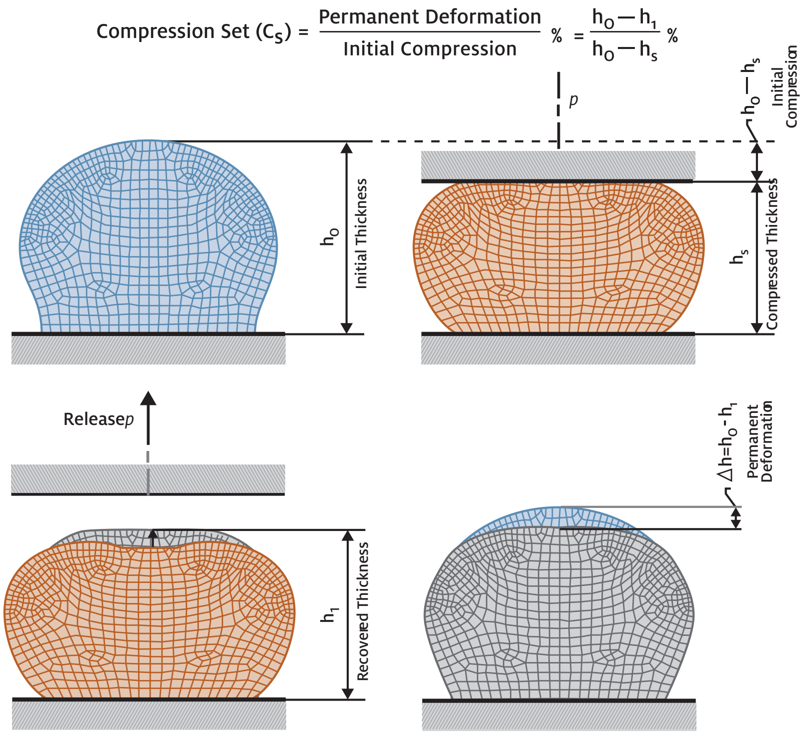


Figure 30: Compression set.

Long-term relaxation behavior and compression set are essentially driven by chemical degradation. They cannot be treated by means of FE analysis, as the continuously changing network density cannot be considered as material property using standard procedures. Their impact on gasket performance is taken directly into account by experimental sealability tests under cyclic thermal loading, representing worst-case operational conditions. Both properties are used to indicate longterm behavior and are subject of customer specifications.

6. Service and repair

6.1. Disassembly

With the correct design, product and process, the joint will maintain the sealing capability throughout the life of the device. Therefore, disassembly will only be necessary for repair.

After disassembling the flange, the compressed CIP sealant can be taken off carefully from a groove, step or standoff design by either:

- pulling off by hand or
- by using a standard tool (spatula) or
- a specific O-ring disassembling tool.

6.2. Cleaning

To seal the joint again, it is important to have clean surfaces to achieve a high-quality seal. After the disassembly of the parts, both flange surfaces have to be cleaned and inspected. Residues like dirt, dust, metal chips or fluid contaminations (oil, grease and powertrain fluids) must be completely removed to avoid contamination of the new gasket and to guarantee good product curing and adhesion to the substrate. In some cases, it might also be necessary to clean parts or areas around the sealed joint.

Recommended Cleaners and Tools (figure 31):

- LOCTITE® SF 7061 (metal flanges only)
- LOCTITE® SF 7063

The use of petroleum cleaners or mineral spirits that may leave residues on the surface is not recommended, since they can prevent adhesion or curing.

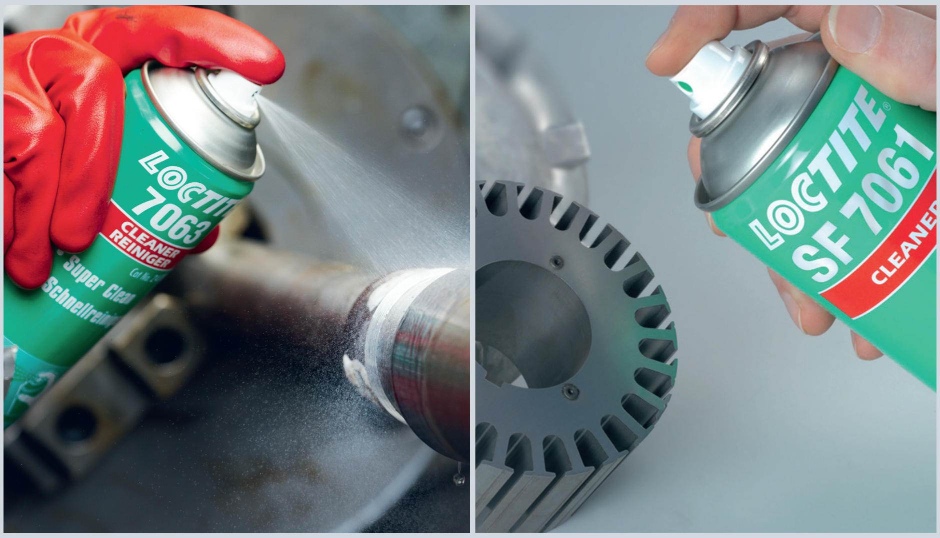


Figure 31: Recommended LOCTITE® cleaners.

6.3. Application and assembly

There are three ways to seal the flanged assembly again:

- by using an elastomeric FIP sealant
- by using a CIP gasket already dispensed on a release substrate
- by using a new part with an integrated CIP gasket, if costs permit (e.g. stamped metal part, plastic lid/cover).

6.3.1. Elastomeric FIP sealants

It is important to describe where the product has to be dispensed and in what quantity. This should be shown in the service manual.

It is important to apply the sealant to only one of the sealing surfaces.

The position, quantity and continuity of the bead should be inspected and any imperfections should be immediately corrected after dispensing. When dispensing elastomeric FIP sealants, it is usually easier to find the proper bead location when the product is applied on the part with the groove or step. For a stand-off design, the elastomeric FIP sealant should be applied as close as possible to the original CIP gasket position.

6.3.2. CIP gasket dispensed on a release substrate

Remove the CIP gasket from the release substrate carefully and assemble it like an O-ring or SGM. If necessary, a Loctite assembly grease can be used for fixation.

6.3.3. New part with an integrated CIP gasket

Assemble the part (e.g. lid or cover) in accordance with the primary (original) production process. The exact procedure should be included in the service manual.

7. Product dispensing and assembly

7.1. Cleaning

CIPG products need clean, dry flanges to achieve a high quality and durable seal. Wet or oily surfaces could reduce the adhesion significantly and affect the tolerances of the dispensed beads (both position and height). This variation will inevitably impact the sealing performance.

7.2. Dispensing

Robot dispensing

The most flexible and reliable way to apply any kind of liquid sealant is by automated robotic systems or by using a XYZ table. Henkel recommends this technology especially for CIP gaskets, since the bead tolerances will influence the sealing performance.

For an accurate application of the product, with a constant height and nearly perfect start and stop points, the dispensing equipment should fulfill the following requirements:

- Tolerance of the bead design, width and height of the bead (including overlap area) +/- 0.1 mm
- Flatness of the work piece at the station 0.10 mm
- Volumetric metering pump with a tolerance of dispensed product quantity of maximum +/- 3%
- Controlling of the metering pump directly linked to the control unit of the robot or XYZ axes
- Linear and continuous variation of the rotation speed of the metering pump proportional to the movement speed of the handling system
- Changing of the rotation speed of the metering pump within a specific time or within a specific distance

7.3. UV curing

Best curing results for polyacrylate products were achieved using mercury arc systems. The spectrum of the lamp must include UVA radiation for the deep curing and UVC radiation to achieve a tack free surface. The quality of the tack free surface depends on the curing distance, UVC amount and radiation dose. The sealant will not become tack free without UVC radiation.

During the UV-curing process, it is common to notice an increase of temperature on the processed parts. To avoid excessive heating, a special reflector is recommended. This reflector allows UV light to be reflected, but absorbs infrared (IR) wavelengths that are much longer. The heat is then dissipated from the reflector surface by air-cooling.

The best results are achieved with following configuration of the curing system:

- Mercury arc system, for example LH10 lamp (Heraeus)
- System power class 240W/cm
- Spectrum of the lamp including UVA and UVC radiation, for example H+ radiator (Heraeus)
- Reflector to reduce the heat on the work piece, for example Dichroic reflector (Heraeus)

8. Scope and limitations

This guideline is based on Henkel's long-standing expertise of over 25 years in application systems and solutions, enhanced by extensive testing performed at the GEC in Munich. With the know-how gained from external collaborations and external collaborations, Henkel is able to demonstrate how a reliable seal can be achieved.

The content should be used to provide assistance during development or to discuss failures occurring in the field. It can also be used to optimize existing flanges.

This guideline may not be used as a substitute for detailed consultation between customers and Henkel's sealing experts. Experience shows that every flange and application is different, and therefore in-depth knowledge of products, designs and processes is necessary to find the best solution for each case.

Exceptions need to be reviewed/examined on a case-by-case basis.

9. Abbreviations

SLS	Single-Layer Steel – A gasket constructed from a single layer of steel. Typically, the steel will include an embossed sealing bead and may incorporate an additional surface coating or treatment.
MLS	Multi-Layer Steel – A gasket constructed from two or more layers of steel. Typically, one or more layers will include embossed sealing beads and the gasket may incorporate an additional surface coating or treatment.
SGM	Soft Gasket Material (including fiber, beater addition, paper, flexible graphite, molded rubber and cut rubber sheet) – A die-cut soft material that compresses to conform to the joint and create a seal. The gasket may additionally be treated with printed beads, surface coatings, sealing grommets, pressed beads or O-rings.
FIPG	Formed-In-Place Gasket – See Section 2 for definition.
CIPG	Cured-In-Place Gasket – See Section 2 for definition.
FIPFG	Formed-In-Place-Foamed Gasket – See Section 2 for definition.
GEC	Global Engineering Center

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