Lead-free for High-reliability, High-temperature Applications

By Hector Steen, Ph.D. and Brian Toleno, Ph.D., Henkel Corporation

Abstract

Though the electronics industry is nearing the three-year anniversary marking the ban of lead from electronics products, several challenges remain with existing lead-free materials for certain applications. The commonly used and accepted tin/silver/copper (Sn/Ag/Cu — SAC) alloy has proven to be a suitable material for production of many devices; however, for those applications that require extremely high reliability, current SAC materials are less than ideal. In particular, devices that will find end use in automotive and military/aerospace products require a lead-free material that can withstand the higher temperatures of under-the-hood conditions, offer vibration resistance not commonly associated with traditional SAC alloys, and deliver high-temperature (>125°C) thermal cycling reliability levels beyond those available with current commercialized SAC materials.

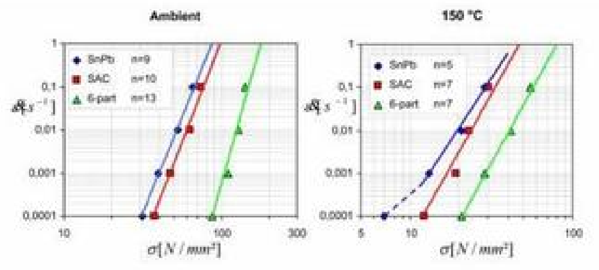
Recognizing these challenges, a group of specialists made up of industry users (Siemens, Bosch, Motorola), materials suppliers (Henkel, Stannol, Cookson, Seho, Infineon, TI, Epcos, Microtech, and Ruwei) and members of the academic community (University of Bayreuth and Fraunhofer Institute IZM) set out to develop an alloy that could meet or exceed the high-temperature, high-reliability requirements necessary for automotive and military applications, yet still be solderable at a reasonable temperature. The project members agreed on the following goals for the alloy. Material must be lead-free. It must work in an operating temperature of up to 150°C. Solder joints should survive 1,000 cycles at -55° to +150°C. The solder must reflow at 230°C or below. Finally, it must meet RoHS standards and be cost-competitive.

Developmental Approach

Analysis of existing alloys and potential modifications to them provided the foundation for this work. Knowledge of the limits of tin/lead alloys and the two most well-known SAC alloys helped drive the direction of the new alloy development. While tin/lead has good high-temperature resistance, it contains a banned RoHS material so is not suitable. Both SAC alloys (SnAg3.5/SnCu0.7 and SnAg3.8Cu0.7) have limited reliability in high operating temperatures. The team established that the required properties could not be achieved with a three-component alloy but would require a multi-element approach. It was decided that SnAg3.8Cu0.7 (SAC387) would be the base alloy and its properties modified to meet the designated requirements by adding additional elements to the mix.

Figure 1. Creep strength of Sn/Pb, SAC, and the six-part new alloy were evaluated at ambient and at 150°C temperatures. The six-part lead-free alloy showed the best creep strength performance.

Fine-tuning the Formula



Using the Coffin-Mansion equation, (Nf)c Δεpl = C, to predict the number of cycles to failure, the hypothesis is that a new alloy that has an activation energy (Δεpl) at 150°C equivalent to the activation energy of failure of Sn/Pb at 85°C and SAC at 120°C, provides the level of reliability required. Since the activation energy for failure is related to the thermal cycling temperature, having the same term for the new alloy at higher temperatures (150°C) as the term for Sn/Pb at 85°C should provide the same level of reliability, e.g., number of cycles to failure.

There are several commonly known methods used to raise the creep resistance of solder alloys, including grain refinement, solid solution strengthening, and precipitation (dispersion hardening/strengthening). Of these methods, grain refinement was ruled out as it is most applicable for lower-temperature applications; solid solution strengthening and precipitation hardening were chosen. Once the methods were determined, a variety of alloying elements were analyzed — three ultimately were selected for their ability to raise creep resistance and maintain an acceptable melting temperature. These included bismuth (Bi), antimony (Sb), and nickel (Ni). The challenge was combining all of the elements in proper balance.

Analysis of creep strength characteristics indicated that the addition of Bi or Sb to SAC387 delivered improved results. Optimizing this property involved fine-tuning the ratio of these elements and Ni in the six-part alloy, and results revealed that the new alloy* provided the required increase in creep strength as compared to either SAC387 or Sn/Pb37 (Figures 1 and 2). The final composition also had to meet the requirement for a reflow temperature in a similar range to that used with conventional SAC alloys. Wetting balance testing was performed to determine the minimum soldering temperature (to be exceeded in the soldering process) at which satisfactory wetting can be achieved. Work was done that shows with the proper ratio of Ni, Sb, and Bi additions to SAC387 good wetting can be achieved, slightly below the optimum solder wetting temperature for SAC387, while maintaining good reliability at high temperatures. The resultant six-part alloy was selected as the most robust formulation with high creep strength and excellent wetting ability. Although the solidus temperature was lowered to 209°C (as compare to that of SAC at 217°C), this did not, in practice, enable reflow at a lower temperature, and hence conferred no benefit of decreased thermal load on the board and the components.

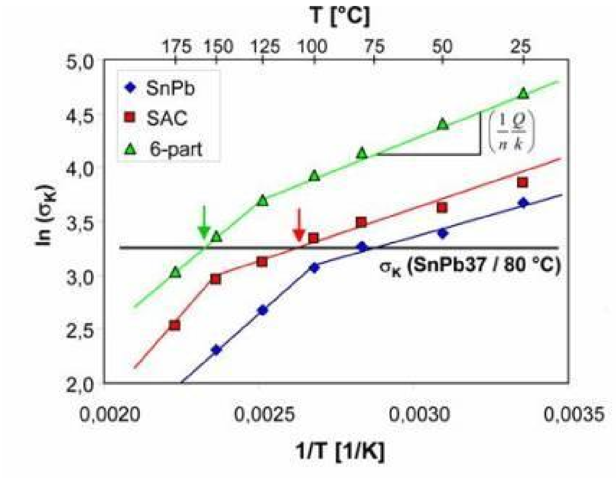


Figure 2. Maximum operating temperature of the six-part alloy was developed so that the new alloy would have the same creep resistance at 150°C as Sn/Pb37 has at 80°C.

Production in High-volume and Subsequent Testing

Manufacturability and metallurgy of the multi-component alloy was then analyzed by the development team. Standard industry-accepted testing including spread, solder balling, thermal cycling reliability, shear strength, vibration, drop, and voiding analyses were all conducted. The alloy showed equivalent or superior performance to that of SAC387 for all tests. Of course, the primary reason for development of the new alloy was to create a material that could withstand higher operating temperatures, so the results of the thermal cycling testing were of particular interest. Figure 3 shows the thermal capabilities of the alloy compared to that of SAC387 and Sn/Pb37. The results of another cooperative project, LIVE, confirmed the alloy's performance was significantly better than SAC and tin/lead alloys in both thermal shock and temperature cycling.

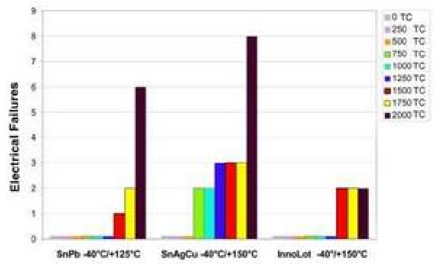


Figure 3. The new alloy shows superior thermal cycling reliability as compared to SAC387 and Sn/Pb37.

Conclusion

The cooperative efforts of industry and academia have resulted in the successful development of a high-operating-temperature, lead-free alloy that reflows at the same temperatures as conventional SAC alloys and will enable increased reliability for certain applications, including automotive and defense. Results from testing of the new alloy show improved reliability in -40° to +150°C thermal cycling versus that of SAC387. In addition, the new alloy offers comparable vibration resistance to that of SAC387, as proven in vibration testing after 500 thermal cycles, and the drop test performance is comparable to that of SAC387.

It should be noted that, because the alloy contains bismuth, manufacturers employing materials based on it must ensure that there is no lead on their components or boards. Lead-terminated components or hot air solder leveled (HASL) finished boards used in combination with the six-part alloy will result in a low melting (98°C) eutectic, which means that joints will fail when exposed to temperatures above about 98°C. There must be no lead in the supply chain when using this material.

The alloy is a promising development for the electronics industry, as continued experience with lead-free materials enables improvements and alterations to meet the emerging requirements of various applications. As with other alloys, the base alloy is only part of the equation. Optimizing solder paste materials for maximum performance will also require flux chemistry expertise and formulation knowledge.

*The alloy developed is under patent proceedings as Innolot.