Enhancing the Ductility of Laser-Welded Copper-Aluminum Connections by using Adapted Filler Materials

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Abstract

Laser micro welding of direct copper-aluminum connections typically leads to the formation of intermetallic phases and an embrittlement of the metal joints. By means of adapted filler materials it is possible to reduce the brittle phases and thereby enhance the ductility of these dissimilar connections. As the element silicon features quite a well compatibility with copper and aluminum, filler materials based on Al-Si and Cu-Si alloys are used in the current research studies. In contrast to direct Cu-Al welds, the aluminum filler alloy AlSi12 effectuates a more uniform element mixture and a significantly enhanced ductility.

Keywords: Laser; micro welding; copper; aluminum; filler material

1. Motivation / State of the Art

In the range of high power electronics more and more so called tailored constructions are established in order to optimize the characteristics of the complete electronic system. Therefore it is necessary to join the respectively most suitable materials for each subsystem to an overall package. In this context, a material connection of particular interest is the combination of copper and aluminum. While copper features an excellent electric conductivity, its high density restricts the possibilities for lightweight designs. Further more, the comparatively high market price of copper leads to a cost increase for electronic constructions. For this reason it is intended to replace copper by aluminum, which features similar electric properties at a reduced market price and a lower specific density. However fusion welding of copper and aluminum leads to an excessive interaction of the base materials and causes intermetallic phases, which feature high hardness values coming along with a distinctive brittleness [1]. While the tensile strength of copper-aluminum connections can be increased by diverse optimization arrangements, such as a systematic enrichment of the aluminum percentage in the welding zone [2] and a laser power modulation [3], the ductility of these dissimilar joints can only be influenced on a limited scale [4]. As a consequence the durability of direct welded Cu-Al joints under alternating thermal loads and chemical exposure is restricted to a certain extent [5]. In this context figure 1 demonstrates the remaining tensile strength of samples welded with different optimization

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methods just after the welding process and after thermal cycling and corrosive load with dilute sulfuric acid. It can be seen that the corresponding optimization steps lead to a considerable gain in tensile strength concerning the as-welded state. On the contrary both in figure 1 presented long-term loads downsize the remaining tensile strength to a level, which is insufficient for electronic applications in mobile systems.

In order to improve the dynamic long-term stability, arrangements for an enhancement of the ductility have to be taken. For this reason the present article points out the potential of increasing the ductility of dissimilar Cu-Al welds by means of adequate filler materials.

2. Basic considerations

For the experimental studies filler materials based on Al-Si and Cu-Si alloys are applied, as silicon features a comparatively good compatibility with copper and aluminum. In particular the filler alloys AlSi12 and CuSi3 are used, which are standardized materials for thermal welding and brazing processes and can be purchased as wire products.

Table 1. Material data of the relevant base materials and fillers according to [6] and [7] - Status of Cu-OFE and Al99.5 semi-hard
Considering the material data given in Table 1 it can be seen that the melting points and the thermal expansion coefficients of CuSi3 and AlSi12 feature values between those of the basic materials. For thermal welding purposes this intermediate position prepares favorable boundary conditions to balance the dissimilar welding properties of copper and aluminum. Major discrepancies in the thermal expansion coefficients lead to high tensile stresses within the welding zone during the cooling down phase, which can rise above the hot yield point of the base materials. In this case a plastic deformation and even the induction of cracks in the weld can be the consequence, so that a compensation of shrinkage discrepancies by the filler material is advisable.

Respecting applications in high power electronics, it has to be mentioned that according to Table 1 the thermal and electric conductivity of AlSi12 is higher than the one of CuSi3 and is more similar to the base materials. Thus for electronic aspects the use of AlSi12 filler seems to be more adequate. However direct Cu-Al connections particularly have issues with an excessive hardness and an embrittlement, the present research mainly deals with an enhancement of the connections’ ductility. Therefore the electric and thermal conductivity of Cu-Al welds with AlSi12 and CuSi3 fillers shall be disregarded within the present paper and will be analyzed during future work.

3. Experimental Setup

For the execution of the welding trials a construction is designed, which allows the accurate positioning of a filler wire between a copper and an aluminum sample. The corresponding experimental setup can be seen in Figure 2, whereat the laser beam derives from a pulsed laser system, featuring a wavelength of 1.064 nm, an average power of 200 W and a focal spot diameter of 400 μm. Furthermore the base material plates made of technical pure aluminum and copper, Al99.5 and Cu-OFE, feature a thickness of 1.0 mm, a length of 50 mm and a width of 10 mm. In order to assure technical zero gaps at the contact line of the filler wire and the base material plates, the latter ones are milled at the front face and cleaned with acetone.

According to Figure 2 the dimensioning of the filler wire diameter is chosen to 1.6 mm, so that an adequate joining gap and an increased coupling of the laser irradiation at the joining area can be realized - especially on the copper side. For a complete connection of both base material plates, two welding steps have to be performed, in which always one base material and the relevant filler wire are connected. On each side of the connection four weld spots with a pitch (distance between two weld spots) of 2 mm are placed, whereby no overlapping is assured and an additional element intermixture between the single weld spots can be inhibited. During the thermal joining process an influence of the atmospheric gases on the fused metal is avoided by using inert shielding gas (Argon) with a flow rate of 5 l/min. After the welding process the down holders of the clamping device can be disengaged, making the samples available for further examinations.

4. Results and Discussion

For each material combination a set of laser parameters is determined, which affects a full penetration of the assembly, compare Figure 3, which exemplary shows connections of Al-AlSi12 and AlSi12-Cu. Based on the joining situation according Figure 2 a steady coupling of the laser irradiation into the samples is realized so that for all implied material combinations a laser power of 2.500 W and a pulse duration of 10 ms are applicable. Due to
aluminum’s higher absorption rate for a laser wavelength of 1.064 nm and a comparatively low melting point combined with a minor thermal conductivity than copper, the weld zone at the aluminum base material side is always more spacious than at the copper side, see figure 3.

![Figure 3. Etched metallographic specimen of an Al-AlSi12-Cu connection welded with 2.500 W and 10 ms](image)

Besides a complete junction of the cross-sectional area without any porosity or cracking, figure 3 reveals the turbulent intermixture of the involved elements in both weld zones. On the contrary to welds with silicon components direct Cu-Al connections, as shown in figure 4 exhibit a minor mixture during the molten state, whereby also the formation of micro-cracks within the weld zone is raised.

![Figure 4. Etched metallographic specimen of a direct Al-Cu connection (Al-plate and Cu-wire) welded with 2.500 W and 10 ms](image)

This increase in element intermixture can be detected at welds with both, AlSi12 and CuSi3 fillers, whereby the effect is more distinctive with AlSi12 filler material. Concerning the micro-cracking within the weld zone AlSi12 affects a significant reduction, while connections with CuSi3 often contain some cracks – however considerably less than at direct Cu-Al welds. Hence it can be noted, that the element silicon leads to a lower viscosity of the molten metal and an enhancement of the melt pool turbulence.

In order to clarify the reasons for the formation of cracks, the micro-hardness of welds with the different filler materials are measured by the Vickers-method. According to figure 5 it is obvious, that direct Cu-Al welds (Cu filler) feature the highest hardness values up to more than 1.000 HV0.05. These maximum hardness values and thereby also the maximum hardness gradients can always be found at the transition area of the weld zone and the copper filler (or respectively the copper base material), where in accordance to binary Cu-Al phase diagram the most
critical intermetallic phases are existent. Further more Cu-Al connections without additional fillers typically show distinctive fluctuations of the hardness distribution via the weld zone.

Figure 5. Random Vickers-hardness measurements of welds with different filler materials. Testing range: from the aluminum base material via the weld zone to the unaffected filler wire. The welds with copper filler material provide a reference.

In contrast to that, the average hardness values of connections with CuSi3 and also the gradients at the transitions zone typically reduce. The most significant decrease of the absolute hardness and its fluctuation can be achieved by using AlSi12 filler material. Hereby the minor fluctuation corresponds with the increased turbulence in the melt pool with especially AlSi12 fillers, resulting in a very thin fluid molten metal and a more uniform element distribution in the weld zone.

For a more detailed analysis of the hardness reduction effect by AlSi12 fillers, element mappings with a microprobe are performed. With this testing equipment it is possible to scan a defined area on the sample’s surface for a certain element. In figure 6 the element copper was searched for and its typical distribution at welds with AlSi12 filler is given in false color rendering.

Figure 6. Microprobe element mapping – copper concentration in an Al-Cu connection with AlSi12 filler

While direct Cu-Al welds always feature high copper concentrations nearby the fusion line at the copper base material, an AlSi12 filler considerably reduces these concentrations to a level of about 50%, see figure 6. In this manner the most critical copper percentages according to the binary Cu-Al phase diagram are limited to a certain extend and the resulting hardness values decrease. Once again, the more turbulent intermixture of the corresponding
elements by the AlSi12 filler can be confirmed by the fine copper dispersion according the element mapping in figure 6.

As the primary objective of the present work is an enhancement of Cu-Al connections’ ductility, 4-point bending tests are carried out in order to analyze the deformability in dependence of the filler material. For this purpose an appropriate 4-point bending tester is constructed, see figure 7.b), allowing a comparison of the different samples’ ductility. At this testing equipment the measured variant is the bending deformation from the initial position to the point of fracture (distance measurement). High bending deformation values suggest a high ductility of the corresponding Cu-Al sample, as an increased deflection can be reached before a cracking occurs. In order to prepare reference bending deformations, direct Cu-Al connections are welded by using copper- and aluminum-wires instead of AlSi12 or CuSi3 fillers with the experimental setup according figure 2. On the basis of figure 7a) Cu-Al reference samples typically reach bending deformations of 0.28±0.06 mm, while the bending deformation can almost be doubled by using CuSi3 filler material. The maximum bending deformation of 0.72±0.16 mm is obtained at Cu-Al welds with AlSi12 filler, which is almost a tripling of the reference value, see figure 7a). The reason for the comparatively high standard deviation of welds with AlSi12 is not yet clarified and will be matter of future work.

Figure 7. Bending test of laser welded samples: a) Maximum bending deformation vs. filler material; b) Assembly for 4-point bending tests

This increase of ductility can also be observed at a SEM micrograph of the fracture surface of samples welded without or respectively with AlSi12 filler material, see figure 8.

Figure 8. SEM micrograph of the area of fracture of Cu-Al weld without (a) and with AlSi12 (b) filler material
According to figure 8.a), the structure of a broken Cu-Al weld spot without an additional filler material appears to be a brittle fracture featuring a high surface roughness without any honeycomb structure. On the other side AlSi12 filler changes the fracture pattern to a more ductile structure with less coarseness and subareas with structures similar to honeycombs, which is typical for ductile separation of metal layers.

Overall it can be recorded, that the use of adapted filler materials offers a significant enhancement of the mechanical properties of dissimilar copper-aluminum welds. In particular AlSi12 filler materials can be recommended for this purpose, as these commercial materials affect a more uniform element intermixture and a reduced average hardness in the weld zone. Thereby the disadvantageous effects deriving from coherent areas of intermetallic phases in direct Cu-Al welds can be decreased and higher ductility values are achievable at bending tests.

5. Summary

The present research indicates that the element silicon increases the fluidity of the molten metal, resulting in a more uniform element intermixture during the welding process. In this manner the local formation of intermetallic phases can be reduced, especially at the copper-sided phase seam in the transition zone of the weld zone and the copper base material. In contrast to direct Cu-Al welds, connections with AlSi12 filler exhibit only negligible micro cracking and reach the maximum bending deformations in a 4-point bending test.

Comparing CuSi3 and AlSi12 filler materials, the higher silicon percentage of AlSi12 reduces the viscosity of the fused metal and thereby the element intermixture in the weld spot more than comparable welds with CuSi3. As a consequence, the recommendation for an enhancement of the mechanical properties, especially the ductility is the use of an AlSi12 filler material.

In future work also the chemical and electric characteristics of Cu-Al welds with CuSi3 and AlSi12 filler will be analyzed, as the material data of both fillers, see table 1, suggest also a more advantageous effect by using AlSi12.

References