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Evaluation of laser braze-welded dissimilar Al-Cu joints

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Abstract

The thermal joining of Aluminum and Copper is a promising technology towards automotive battery manufacturing. The dissimilar metals Al-Cu are difficult to weld due to their different physicochemical characteristics and the formation of intermetallic compounds (IMC), which have reduced mechanical and electric properties. There is a critical thickness of the IMCs where the favored mechanical properties of the base material can be preserved. The laser braze welding principle uses a position and power oscillated laser-beam to reduce the energy input and the intermixture of both materials and therefore achieves minimized IMCs thickness. The evaluation of the weld seam is important to improve the joint performance and enhance the welding process. This paper is focused on the characterization and quantification of the IMCs. Mechanical, electrical and metallurgical methods are presented and performed on Al1050 and SF-Cu joints and precise weld criteria are developed.

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Keywords: laser; dissimilar; braze-welding; aluminum; copper; evaluation

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1. Introduction

The main challenges for the automotive industry are reducing energy consumption and emissions, e.g. by reducing weight and cost of wiring harnesses. Dissimilar aluminum-copper connections could be used to achieve these goals, as described by (Bergmann, et al., 2013). Furthermore, the joining of Li-Ion battery electrodes, usually made of Al and Cu, is a key technology for manufacturing battery electric vehicles.

The welding of non-solvable dissimilar metals, such as Al and Cu, is considered as difficult because of the inevitable formation of intermetallic compounds (IMC). Based on partial covalent and ionic connections, IMC are energetic more stable than pure metallic connections (Worch, et al., 2011). Thus, IMC are hard, weak conductors, see table 1, with reduced elongation properties. Aluminum and copper are two dissimilar metals with reduced

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solubility, the thermal joining will cause brittle joints with higher resistance. In addition, the different melting point and thermal expansion must be considered, as well as the electrochemical corrosion (Kannatey-Asibu, 2009).

In order to maintain the desirable properties ductility and toughness of the metallic base material, the formation of IMC should be avoided. Due to the fact that a material connection of dissimilar metals demands IMC, they cannot be eliminated, but it was shown, that the minimizing of the IMC thickness results in high quality joints, shown by (Borrisutthekul, et al., 2007), (Abbasi, et al., 2001) and (Solchenbach, et al., 2013).

Table 1. Properties of intermetallic phases in the Aluminum-Copper system.

Phase	Nominal composition	% at Al. (Murray, 1985)	Electrical resistivity ρ at 20° C [µΩ cm] (Rayne, et al., 1980)	Hardness HV (10g) (Solchenbach, et al., 2013)	Hardness (Braunovic, 1994)	Hardness HV (Chen, et al., 2007)
(Cu)		0-19.7	2.0	75	-	70
γ	Al_4Cu_9	31-37.5	14.2	770	-	750
ζ	Al_3Cu_4	43.7-44.8	12.2	930	624	850
η	AlCu	47.6-50.2	11.4	905	648	900
Θ	Al_2Cu	67-68.1	8.0	630	413	650
(Al)		97.52-100	2.4	36	-	35

The minimizing of the intermetallic layer can be performed by minimizing the intermixture of the metals and reducing the process time to avoid diffusion. Regarding the solid-state fusion processes (Hügel, et al., 2009), the laser welding presents the advantages of contactless power delivery and fast process times based on the low-inertia positioning system. Copper and Aluminum can be joined by using filler material (Weigl, et al., 2011) or roll-cladded inserts (Weigl, et al., 2010). We will focus on the braze-welding principle (Solchenbach, 2014), which will be explained in the next chapter.

In order to evaluate the quality of a welded joint, the classical pull test can be performed. More dedicated methods to analyze the formatted IMC are described by (Mai, et al., 2004), who used cross sections and x-ray photographs to investigate the mixing behavior, the microstructure and the presence of defects, such as cracks. Based on the electric resistivity of the IMC, a resistance measurement can reveal the joint quality, as shown by (Solchenbach, et al., 2014). The author showed that a low resistance of the weld is equivalent to good mechanical properties. SEM and EDX was used by (Xue, et al., 2013) to characterize the melt pool and to build up a simulation model for attributes prediction. (Weigl, et al., 2011) used a hardness measurement method to rate the sensitivity of the weld towards cracks and to evaluate the ductility of the joint. They declared the joint with lowest hardness as the most ductile, which was also confirmed by fracture surface analysis and bending tests.

In this paper, methods to evaluate the quality of a laser welded dissimilar Al-Cu joint will be described. Current methods will be enhanced and adapted for the braze-welding process. The goal is to use the evaluation methods to rate the overall quality of dissimilar Al-Cu joints. The methods will be described in chapter 2 as they were used in chapter 3 to perform the experiments.

2. Experimental setup / methods

2.1. Braze-welding

The braze-welding principle is a modified laser welding process based on the keyhole welding principle, which is described by (Dowden, 2009). The formation of brittle IMC is minimized by reducing the intermixture of both metals. The aluminum sheet is positioned in overlap configuration on top of the copper sheet, see Fig 1 (a). The aluminum is liquefied by the introduced laser energy while the copper remains in solid state. Thus, a minimized fusion zone between both materials is formed and the formation of IMC is limited. The width of the fusion zone is defined by a spatial oscillation and power input by power modulation, see Fig. 1 (b). (Solchenbach, et al., 2013) showed that the IMC thickness can be limited to 3.4 µm, thus achieving high joint strength and reduced electrical resistance.

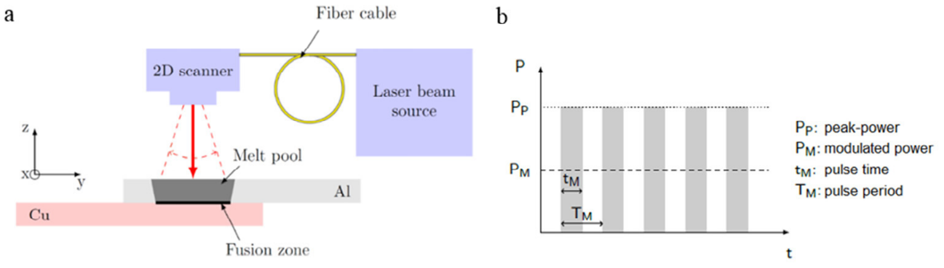

Fig. 1. (a) Laser braze-welding principle; (b) laser power modulation.

During the investigations, 0.2 mm thick Al 1050 (Al 99.5) was welded to 0.5 mm Cu (SF/E-Cu). A fiber laser (TruFibre 400) with 1070 nm wavelength with focal diameter of 33 µm was used as energy source and a HurryScan Optic for beam positioning. The samples of 40x40 mm were welded in overlap configuration with 30 mm joint length. The spatial oscillation was set to achieve a weld seam width of 0.5 mm with an oscillation frequency of 500 Hz and the laser beam was pulse-width modulated with 18 kHz and varying pulse times from 24 to 48 µs in 3 µs steps. The feed rate in x-direction was 50 mm/s and the maximum laser power of 400 W was used.

2.2. Mechanical tests

A lap shear pull test was used to determine the mechanical properties of the joint. The maximum pulling force and toughness were used to describe the mechanical performance. The pull tests were performed with 6 samples for each parameter set. The toughness was calculated by integrating the maximum pulling force as a function of the elongation. Laser-braze welded joints achieve mechanical pull forces up to 90 % of the weaker base material (Median pulling force 0.2 mm Al with sample geometry as Fig 2,b of 331 N), causing high deformation of the base material whereby cracks at the start- and endpoint of the weld seam where formed, see figure 2,a. The start- and endpoint of the weld seam were punched off, reducing the standard deviation for the maximum pulling force for welded joints from 3.8% to 1.8 %. The standard deviation for toughness was reduced from 18% to 10 %, see Fig 2,c. The average toughness decreased with the improved geometry, since the deformation of the base material (case a) absorbed energy too.

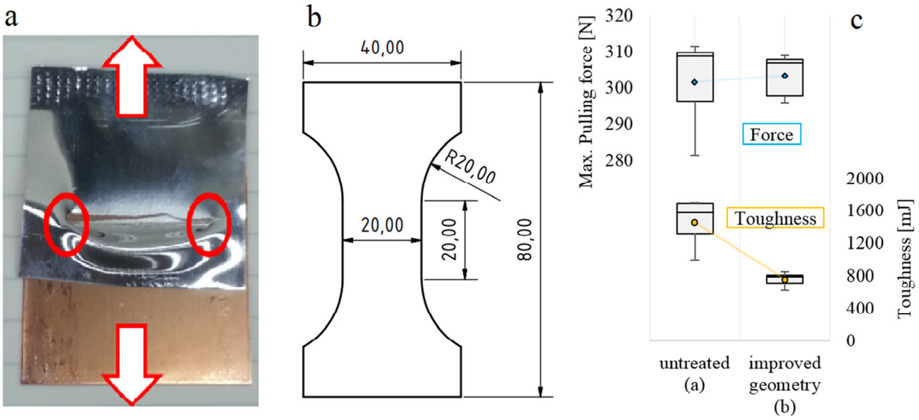

Fig. 2. (a) crack starting from the weld seam ends; (b) improved sample geometry, achieved by punching; (c) enhanced accuracy of pull test of welded samples.

2.3. Metallographic analysis

The microstructure of the weld seam is analyzed by metallographic cross sections. To prepare the cross sections, the weld seam was cut and embedded in plastic, grinded with 1000 SiC paper and polished down to 1 µm diamond suspension. The samples were etched according to (DIN V 1739, 1996) with the Keller reagent. Fig 4, a shows a typical cross section of a laser braze-welded Al/Cu joint. The weld seam appears darker than the surrounding material because of the chemical attack of the etchant, which mainly attacked the θ-phase Al_2Cu. In Fig 3, b a thin layer of η-, ζ- and γ-Phase with a thickness about 20 µm thick (red lines) was found. This interface has also been investigated by (Chen, et al., 2007).

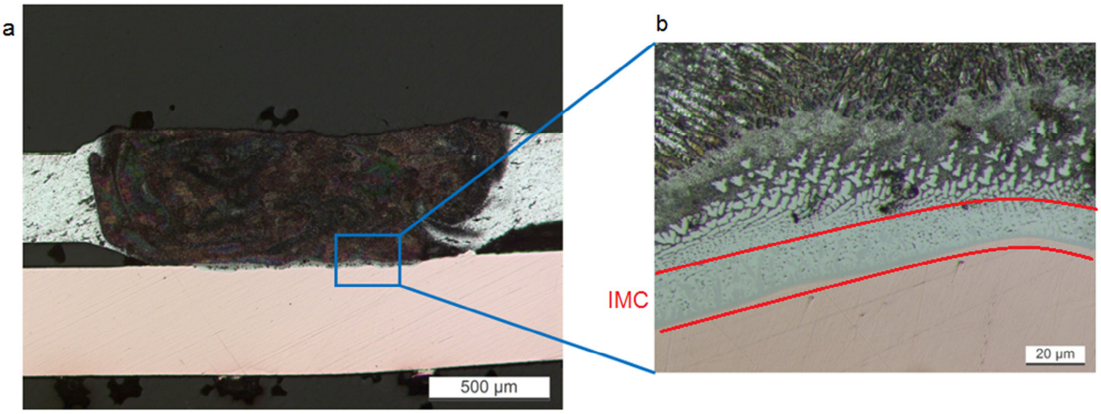

Fig. 3. (a) Laser-braze welded Al/Cu joint with 27 µs puls time; (b) thin IMC of ±20 µm thickness with critical θ-Phase (Al_2Cu) and γ-Phase (Al_4Cu_9).

The hardness was measured in the partially respectively fully developed ζ-Phase (Al3Cu4) and η-Phase (AlCu) because of their increased hardness compared to the ductile base metals, see table 1. These intermetallic phases were found to be most critical for joint quality, due to the propagation of cracks through these phases in the cross sections, which was also found by (Chen, et al., 2006). The phases were identified on the cross-section by their dark grey/brown color. The hardness tests were performed based on the Vickers method with a load of 300 gf (DIN 6507, 2005). The 10 indentations with highest hardness for each parameter set were evaluated.

2.4. Electric tests

The IMC have an increased specific electric resistance ρ, which is about 4 to 7 times higher compared to copper or aluminum (see table 1). It was shown that an increasing interface resistance is in correlation with a decreasing shear strength (Solchenbach, et al., 2014). The resistance was measured using the four-wire method, see Fig. 4a. The method requires two wires for inducing a high current and two separate wires for measuring a voltage drop on the sample. Since the measuring wires do not conduct the high current, the resistance of these wires are negligible and low resistances up to µΩ can be measured. According to previous studies, a comparable method can be used to measure the electrical contact resistance of different welding techniques, whereby laser weld seams achieve minimal resistance (Brand, et al., 2015). According to the braze-welding principle, the amount of IMC must be minimized, whereby the share of the IMC on the total weld resistance is minimized too. Hence, a new measurement device was developed to provide more accurate resistance measurements. The electrodes were directly placed on top of the weld seam to avoid current bypasses and to keep the serial resistance of the base material as small as possible, see Fig. 4b. Furthermore, the electric measurement is a fast, nondestructive method to analyze the joint quality.

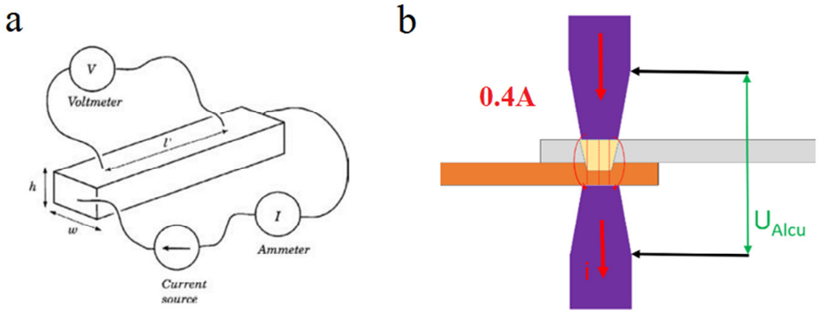

Fig. 4. (a) four-wire method to measure small resistances, by (Heaney, 2000); (b) direct electric IMC measurement method.

The electrodes were made of CuCrZr, a material also used for spot welding electrodes. The influence of contact resistances was analyzed by comparing measurements with and without thermal compounds with high electric conductivity on the electrodes. No notable advantage was found, therefore the tests were performed without contact compound. A direct electric current of 0.4 A was applied and the electrodes were pneumatically actuated to assure a constant clamping force. Each weld seam was electrically measured 15 times.

3. Results and discussions

The highest median pulling force of 303 N was achieved with a pulse time of 24 µs, see Fig 5. The median pulling force is approx. 90% of Al base material strength (331 N) for pulse time 21-30 µs, before decreasing to approx. 70% for pulse times 39-48 µs with a successively increasing variation. This phenomenon can be explained by the increasing amount of IMC, causing a brittle weld seam, which has also been observed during pull test. The highest median toughness of 837 mJ was achieved for 21 µs pulse time. Both results show stable and best mechanical performance for pulse times 21 µs to 30 µs, where the energy input and thus the IMC width is minimal, as shown by previous studies (Borrisutthekul, et al., 2007), (Solchenbach, et al., 2013) and (Mai, et al., 2004).

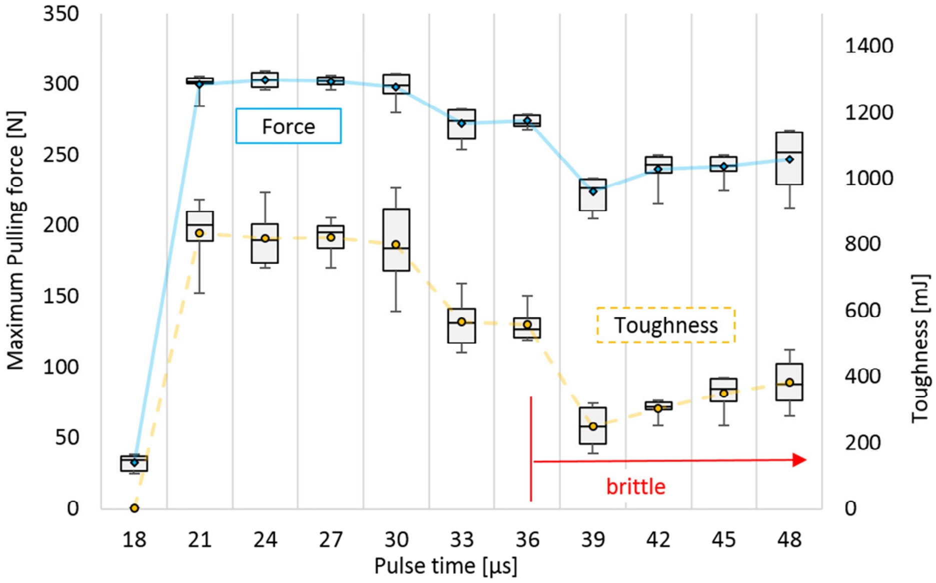

Fig. 5. Evaluation of Al/Cu joint with varying energy input by means of max. pulling force and toughness.

The maximum pulling force and toughness are strongly correlated, the highest force being achieved with equal parameters as highest toughness. The toughness offers a significant advantage to the force by taking the elongation into account, thus the brittleness of the weld seam is more likely to be detected. The pulling force dropped about 25% from 27 µs to 39 µs, whereas the toughness dropped for identical process parameters about 70%. The toughness therefore is a more precise value for evaluating mechanical performance. Furthermore, the results show the presence of a distinct process-window, here 21 to 30 µs pulse time. Hence, the goal of minimizing IMC can be refined to a more practical threshold, underneath a ductile break behavior is achieved, e.g. a minimal toughness of 700 mJ in these investigations.

3.1. Hardness test

According to table 1, the hardest phases are the ζ-Phase (Al_3Cu_4) and η-Phase (AlCu) with about 900 HV. A maximum hardness of 805 HV was measured for a pulse time of 48 µs, see Fig 6. The base materials had a hardness of 21 HV (Al) and 110 HV (Cu). The intermixture increased strongly for more than 27 µs. For 24 µs pulse time, the weld had a median average of 144 HV. The hardness increased constantly with higher energy input.

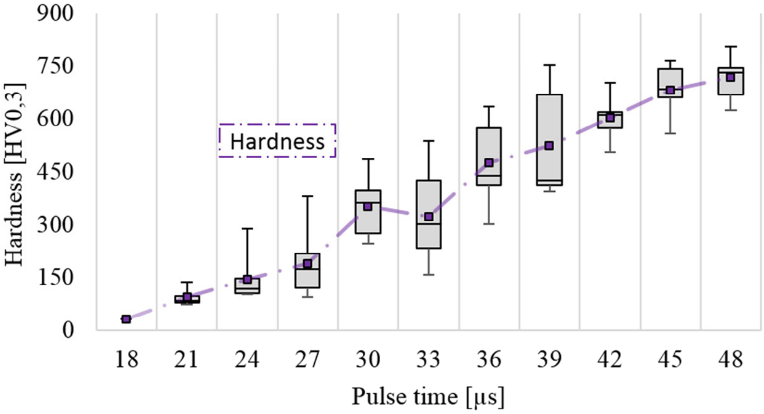

Fig. 6. Evaluation of Al/Cu joint with varying energy input by means of hardness HV 0.3.

When measuring hardness above 500HV, the indentation caused fissures and cracks, see Fig 7. The cracks mainly propagated through the ζ-Phase and η-Phase, as discussed in section 2.3.

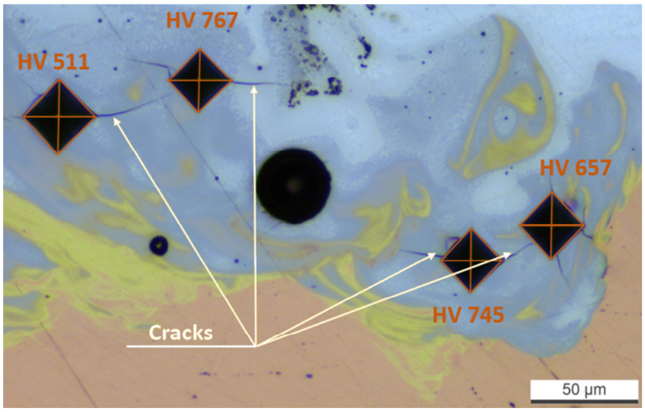

Fig. 7. (a) Hardness test on Al-Cu welds with 45µs pulse time, the main cracks were found in the ζ-Phase (Al3Cu4) and η-Phase (AlCu).

By comparing the mechanical results and the hardness, it was found that a hardness above the threshold value of 350 HV has a negative influence on the weld performance. Furthermore, hardness values of 80-170 HV (21-24 µs) are interpreted as a indication of a well-developed interface with good mechanical performance.

The indentation size is directly linked to the applied force and has an averaging character. A higher test force results in a bigger indentation size, thus reduces the influence of small IMC to the measured hardness. A hardness of 805 HV is equivalent to 26,2 µm diagonal of the Vickers diamond pyramid for a load of 300 gf, calculated by equation 1 (DIN 6507, 2005). The maximal expected hardness of approx. 900 HV hence is equivalent with an pure IMC width of at least 25 µm. Usually, an IMC thickness of 2-5 µm can allready be seen as critical for weld seam brittleness (Braunovic, 2007). Here, a hardness above 500 HV (39-48 µs) was found to be critical for weld seam brittleness.

$$HV = \frac{2 \cdot F \cdot \sin(68°)}{d^2} \tag{1}$$

For micro-hardness (less than HV 0.3) tests, the hard phases are more likely to be detected, since the indentation size is reduced. Therefore, a higher averaged hardness is acceptable. Macro-hardness tests (more than HV 0.3) are forming a mean value of the larger area, thus result in lower maximal acceptable hardness values.

3.2. Electrical test

For a pulse time of 24 µs, a minimal median resistance of 204 µΩ was measured, see fig 8. The unwelded Al sheet on a Cu sheet (shown in the diagram with pulse time 0 µs) had a higher median resistance of 1.85 mΩ. The resistances for 39-48 µs pulse time were 2-3 times higher compared to 21-27 µs pulse time with significant higher resistances outliers. These weld seams were found to be brittle (see mechanical test 3.1), therefore cracks and pores were responsible for the outliers.

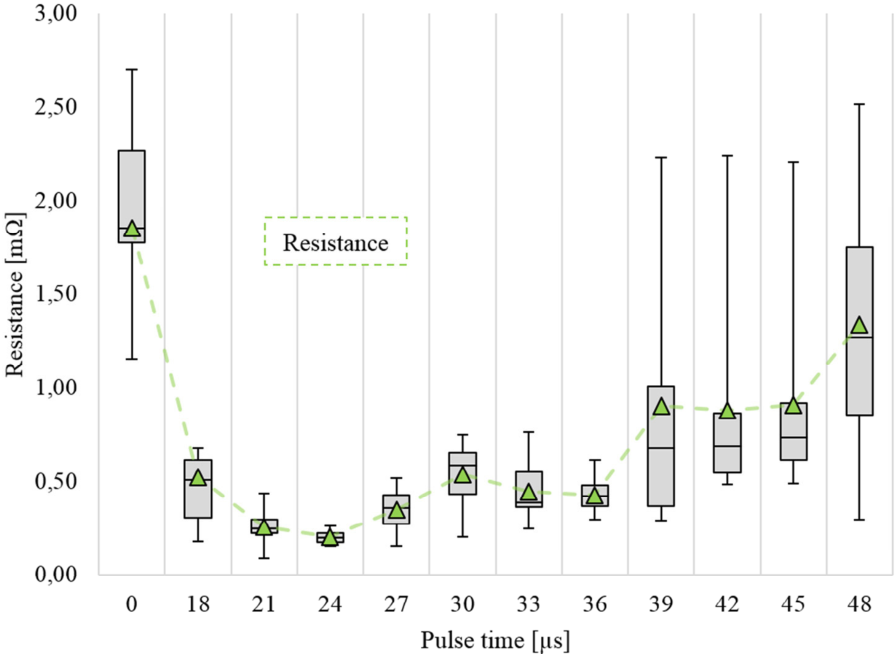

Fig. 8. Evaluation of Al/Cu joint with varying energy input by means of electrical resistance, 0 µs pulse time is for unwelded materials.

The weld resistance increased with the presence of more IMC in the weld seam. From 24 to 30 µs pulse time, this behavior can clearly be detected, but from 30 to 36 µs pulse time, the median resistance decreases lightly. An indirect measurement of the IMC thickness based on resistivity measurement is therefore difficult, the variance of the measurement device is too high. The intermetallic interface has no consistent layer thickness, i.e. the intermixture is too agitated for pulse time above 30 µs. The resistance for the unwelded base material (pulse time 0 µs) was 9 times higher than the resistance for a 24 µs pulse weld (204 µΩ), which evidences an increased transition resistance between Al and Cu, compared to welded joints. A resistance of more than 500 µΩ presents a threshold for a joint with poor mechanical properties, caused by either cracks, pores or insufficient connection.

4. Conclusion

The evaluation of Al-Cu welds based on mechanical, hardness and electric tests were described, they indicate detailed information about the performance of the joint. The results from the different tests are strongly linked and were interpreted to make conclusion about the heat input and how laser parameters have to be adapted:

- In order to increase the joint mechanical performance, the material intermixture must be minimized. Here, a dedicated process-window (pulse time of 21 to 30 µs) was found which gives a good process robustness.
- The toughness is a better criterion for weld seam evaluation than the pulling force, since it takes the elongation, and therefore the ductility/brittleness of the connection into account.
- By increasing the IMC layer thickness (pulse time more than 36 µs), the weld becomes more brittle and the joint performance becomes more unstable, shown by the electric resistance and pulling forces.
- Three quality criteria for a strong connection were identified and used as a threshold to classify the weld quality in satisfying or not. They were a minimal toughness of 700 mJ, a maximum hardness of 350HV in the fusion zone and maximum resistance of 500 µΩ.

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