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Laser overlap joining from copper to aluminum and analysis of failure zone

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Abstract

Joining of copper and aluminum sheets are very crucial for battery application. When joining from copper sheet, keyhole mode of welding is essential to overcome the reflectivity and melting threshold of copper. However, in dissimilar material interaction the resulting intermetallic (IMC) phases are brittle, which result in reduced performance.
This paper analyses the joint with laser beam irradiated from the copper side (Cu on top). The idea is to distribute the intermetallic compounds inside the joint to obtain a ductile behavior. The zones of failure and the distribution of the intermetallic phase is studied. The microstructural analysis of the fusion zone and mechanical strength of the joint are presented.

Keywords: Battery application; Aluminium-copper joints; Laser welding;failure analysis; Intermetallic compounds.

1. Introduction

The laser welding for automotive applications is interesting as it offers rapid processing speeds and are highly automatable for future industrial revolutions(Brand et al. 2015). One important automotive application is in dissimilar joining of thin sheets for electro mobility, example joining Al and Cu(Hong and Shin 2017). A well-known issue with the Al-Cu system is the brittleness of the joint, which are attributed to formation of brittle intermetallic compounds (IMC). Laser welding is a thermal process, which joints the work piece by melting the material and subsequent solidification to produce a joint.

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The IMC formation is favored by the introduction of temperature as laser welding process often exceeds the melting point of the joining materials. In the aluminum- copper system as shown by (Abbasi, Karimi Taheri, and Salehi 2001),(Braunovic, Rodrigue, and Gagnon 2008) the intermetallic compound formation is ordered in Al-Cu system. In combined laser-braze welding process authors in (Solchenbach and Plapper 2013) showed the presence of only Al2Cu and Al4Cu.But with high resolution, XRD analysis conducted with synchrotron radiation source it was shown that a wide variety of IMC exist(Schmalen et al. 2018). Therefore limiting the thickness of the detrimental phases are some approaches to improve ductility of the Al-Cu joint (Fetzer et al. 2016)(Solchenbach and Plapper 2013). However, completely getting rid of the intermetallic phases is unrealistic considering the thermal nature of the process and the rapid cooling rate.

In this paper, the laser joining process for Cu-Al (copper on top) is investigated. There is only a scarce number of publications for this configuration (Rudlin, Bono, and Majidnia 2014)(Leitz 2015)(Xue et al. 2013) and the interaction of Cu-Al and phase formation is not well studied (Jarwitz et al. 2014). From the investigations, Copper (Cu-Al) on top configuration also yields comparable shear strength as Al-Cu (Al on top). Therefore, the question of configuration change (i.e Cu on top) in Cu-Al system needs methodology and scientific explanation. In this configuration, the laser beam irradiation on the copper sheet requires a very high intensity in the order of 10^7 W/cm^2 in order to overcome the reflectivity issues of copper with infrared laser wavelength. Such a high level of intensity rises the effective temperature of the welding process. In this configuration, the idea is not to completely avoid the formation of intermetallic phases but to control them and distribute them in a discontinuous fashion inside the weld cross-section. In this paper, the beam oscillation technique in form of infinite profile is successfully utilized to produce a ductile behavior of joint system. Different regions of failure is classified after the tensile shear test and the microstructural analysis is performed for the weld cross-sections.

2. Experimental

A simple schematic of the process is depicted in the Fig 1 (a). For the laser welding experiment disk laser of wavelength 1030 nm with maximum power of 2000W is used. All the samples used were annealed aluminum (Al 1050) and copper (CuOF) sheets with thickness of 600µm welded in overlap configuration with copper placed on top and aluminum in the bottom. Throughout the investigation laser beam was focused on the top of Cu with the spot diameter of 89µm.During the experiments no shielding gas was used but cross jet was employed to protect the scanning optics system.

Table 1. Specification of materials for laser joining experiments

Material	Grade	Thickness [mm]	Coating	Dimension [mm]
Copper	99.95% pure- oxide free	0.6	No coating	40 × 45 mm
Aluminum	1050 Al	0.6	No coating	40 × 45 mm

The laser beam oscillation in form of infinite loops with amplitudes 0.75mm(2a=1.5), 0.875mm(2a=1.75), 1mm(2a=2) are used. The oscillatory motion in X and Y coordinates is defined as shown in Fig 1 (b).The frequency and the velocity of wobbling is fixed to 100Hz and 50 mm/s . The laser power for investigation is in the range of 950 W to 1800W.

Fundamentally, beam oscillation help to increase the weld widths with a highly focused laser beam. Enlarging the welding width using a highly focused laser beam allows for overcoming the melting threshold of highly reflective materials like copper. The high intensity of laser beam helps with formation of keyhole to couple energy efficiently into copper and with oscillation, a larger weld zone is obtained. This particular oscillatory trajectory is selected because of is vigorous profile to produce a rapidly moving heat and fluid flow of molten material inside the seam. Detailed results of the oscillatory motion is discussed in sections 3.1 and 3.3 with macroscopic and microscopic images of the weld bead.

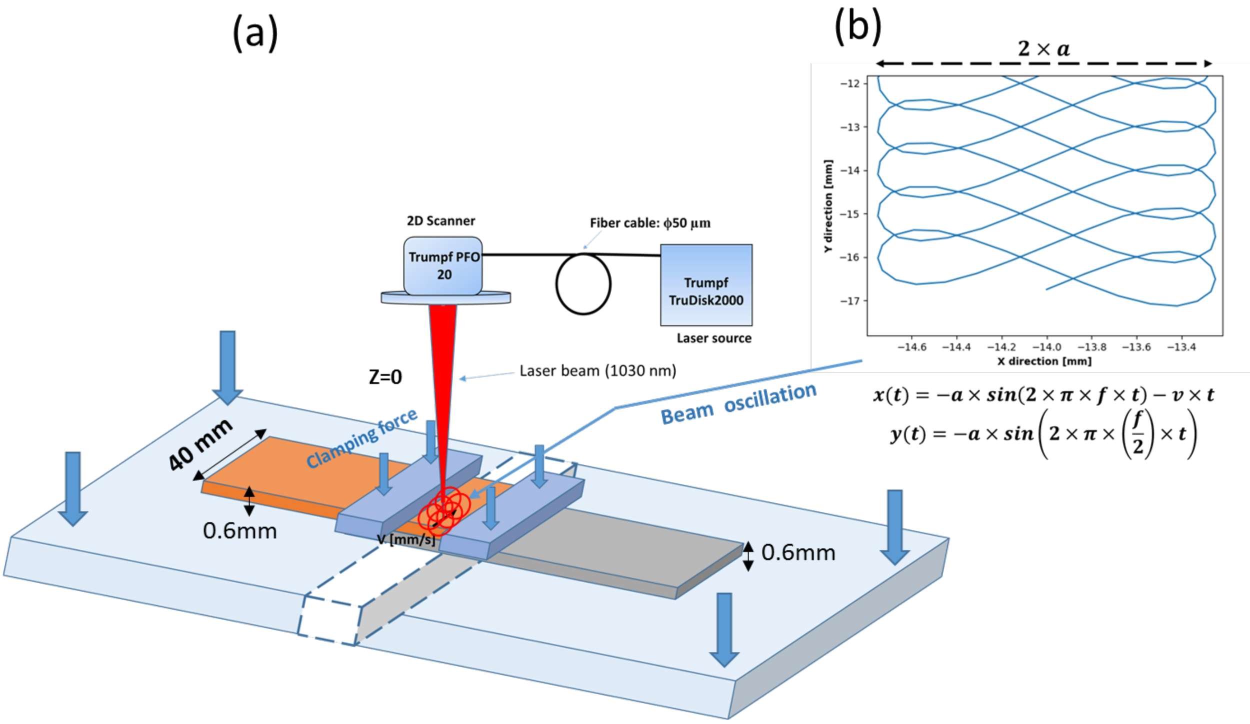

Fig. 1. (a) Sketch of laser welding setup for copper on top and (b) Laser beam oscillation profile in form of infinite loops

3. Result and discussion

3.1. Bead on Cu-Al

The bead on copper plate takes the shape of laser beam trajectory shown in Fig 2. The bead development on the top of copper is proportional to the laser power. For high, power of 1500 W a large oxidation on copper plate extending from the fusion zone. Conversely, bead development is inversely proportional to the oscillation width. For the laser power of 1000W, for low oscillation widths 1.5 and 1.75 mm, a connection between Cu-Al is obtained. However, for higher oscillation width of 2 mm there is no connection at 1000W and weld bead is not fully developed. As the oscillation width increase, a higher power is required to produce a developed weld bead. Alternatively, the feed velocity and frequency can be adjusted to compensate for the power demand but at high frequency, the hardware limitation of the scanner must be taken into consideration. Based on the macroscopic pictures (Fig 2) of the bead on Cu-Al joint, the surface pore generation or spatter on top of the weld seam is negligible or absent for the infinite oscillation profile for the power ranges 1000W to 1500W.

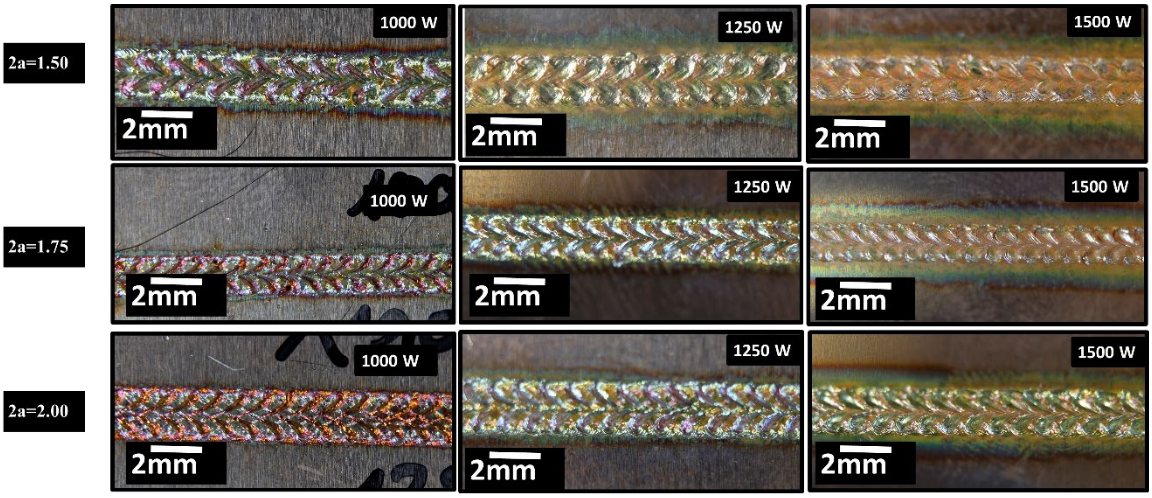

Fig. 2. Bead on copper plate for different power and wobbling amplitudes

The microscopic image in Fig 3 for fixed feed velocity of 50 mm/s, oscillation width of 1.5 mm and for laser powers (a) 1250W and (b) 1500 W shows the fusion zone mixing from the successive trajectories. The laser feed direction is shown in the red dotted line and oscillation profile is marked in white arrow. This

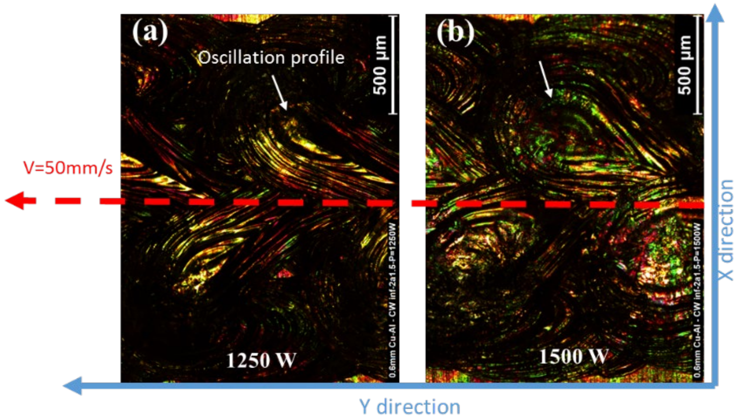

Fig. 3. High magnification of the Cu-Al bead for oscillation width of 1.5 mm, feed velocity of 50mm/s (a) P=1250 W and (b) P=1500W.

particular oscillatory motion results in a vigorous mixing path in X,Y directions as shown in Fig 3 (a) & (b).For power of 1500W the oscillation profile is larger and a vigorous mixing of fusion zone from the previous track is evident. Even at high magnification, no blowholes or surface cracks are noticeable for the particular oscillatory profile with the tested process parameters.

3.2. Shear strength

The shear strength of the joint expressed in terms of force (N). The exact resisting area depends on the failure location and calculation of absolute fusion area is tedious and micro variation of the seam geometry. The shear strength of the joints were tested in a standard tensile shear test machine with clamps to hold the sheets, which has a maximum pull force of 5KN. The beam oscillations with width of 1.5 mm, 1.75mm and 2 mm are studied with fixed oscillation frequency of 100Hz and feed velocity of 50 mm/s. Large oscillation width reduce the depth of weld and lead to a larger fusion zone area. The laser power is varied in order to study the fusion zone. For power less than 950 W there is no joint. As the oscillation amplitude gets large, higher power is required. For oscillation width 1.75mm the minimum power for a joint was 1000W and for 2mm the minimum power required was 1250 W. In copper to aluminum joint, the trend of the shear strength is that for low power the shear force is low then it increase to a maximum value and further increasing the power activates more copper and aluminum. This high power activation results in a larger weld fusion zone and formation of detrimental phases all over the fusion zone. Such a joint with high laser power lead to a decreasing shear force.

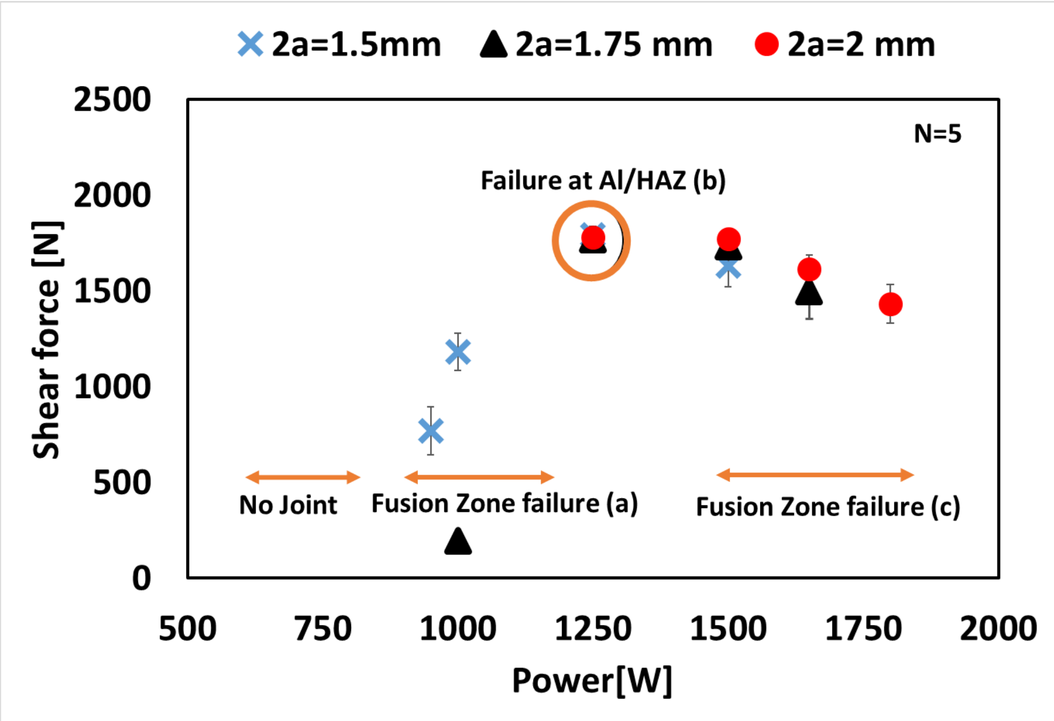

Fig. 4. Shear strength in Newton for Cu-Al joints (copper on top) for different power and oscillation widths of 1.5, 1.75 and 2 mm.

The shear strength for power of 1250W is about 1800N, which is nearly the same as the base aluminum sheet. Therefore, in Cu-Al configuration for infinite oscillation profile the joint is nearly strong as the base aluminum sheet. From the mechanical response of the joint it can be seen that a maximum condition exist for the Cu-Al configuration similar to the Al-Cu condition. However, at the maximum condition for Cu-Al joint the intermixing is significantly higher than in Al-Cu (will be discussed in the next section). The distribution of phases with a combination of ductile and brittle intermetallic structures result in the ductile behavior for the copper to aluminum joint. This type of oscillation is beneficial in distributing the IMC phases as the fluid flow and resulting fusion zone follows the trajectory of the laser beam.

3.3. Microstructure

The cross-sections of the Cu-Al joint were analyzed to study the effect of the laser beam trajectory on the fusion zone. Presence of porosity on the cross-sections are due to fact that no shielding gas is used. The porosity is likely formed on the aluminum side of the fusion zone. From cross-sectional micrographs, a linear relation of the weld depth for increasing power. The fusion depth and width in Cu-Al joint are proportional to the laser power input. However, for the Cu-Al joint the intermixing is very rapid as the difference in density and the melting temperature is very large. The beam oscillation naturally provides a discontinuous fusion zone where the depth is changing in cross-sectional direction. For the joint with maximum shear strength i.e. P=1250W at oscillation width of 1.5 mm, depths d1, d2 and d3 is formed in the weld fusion zone as shown in Fig 5 (a). For this condition, the failure is not at the fusion zone but away from the weld fusion zone most likely in the heat-affected zone of Al. Therefore, despite the presence of complex brittle intermetallic

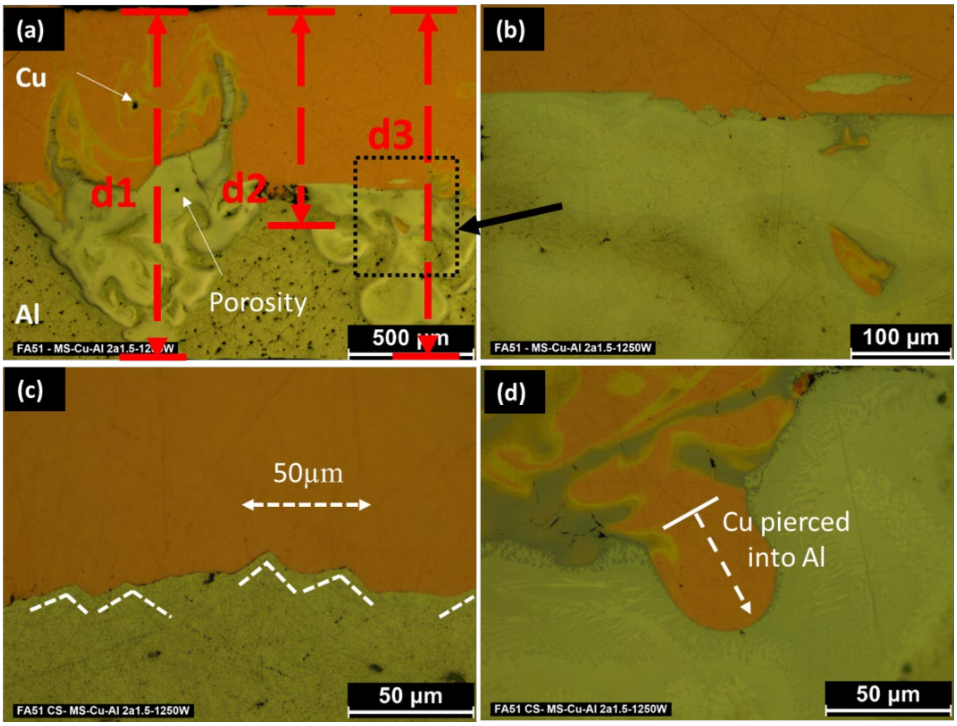

Fig. 5. Micrograph of Cu-Al joint with beam oscillation width of 1.5 mm and P=1250W (a) Cross-sectional view of the weld seam (b) Fragments Al and Cu due to the rapid fluid pressure of laser and beam oscillation (c) &(d) microinterlocking at the interface

structures, the joint is strong and a significant plastic deformation of the aluminum takes place. Explanation to a large plastic deformation away from the joint in aluminum is formation of discontinuous weld depths d1, d2, and d3. Regions d1 and d3 with depth of 500-600 µm into aluminum result in highest level of mixing and formation of dendrites that are of complex intermetallic phase composition.

The region with depth d2 (about 75 -200µm) into Al result in a lower mixing of Cu and al. The result of depths d1, d2, and d3 is that the seam formed is a combination of areas with high level of mixing and low level of mixing. Such variation corresponds to a combination of ductile and brittle phases. The region d2 is the zone of very low level of cu-al mixing. In this region, a sort of saw tooth interface and piercing of copper melt into aluminum side (Fig 5 (c)) is realized indicating the possibility for mechanical locking.

Therefore, a discontinuous distribution of IMC compound obtained with a combination of highly intermixed zone and region with minimal Cu-Al diffusion. Such a joint provides a combination of ductile and brittle phases inside joint. As a result, a higher shear strength of joint despite the presence of large intermixing.

3.4. Failure

In this section, the Cu-Al joint is analyzed after the tensile shear test. The failure mode is classified for the Cu- Al joints based on the location of the failure i.e (a) Failure at the interface of the fusion zone, (b) failure away from fusion zone, (c) failure in the fusion zone i.e. separation at the edge or at the weld centerline. The schematic of the joints with copper on top and aluminum in the bottom is depicted in Fig 6 on the left side. The Cu and al sheets after failure is on the right side. Based on the failure location the interface view is

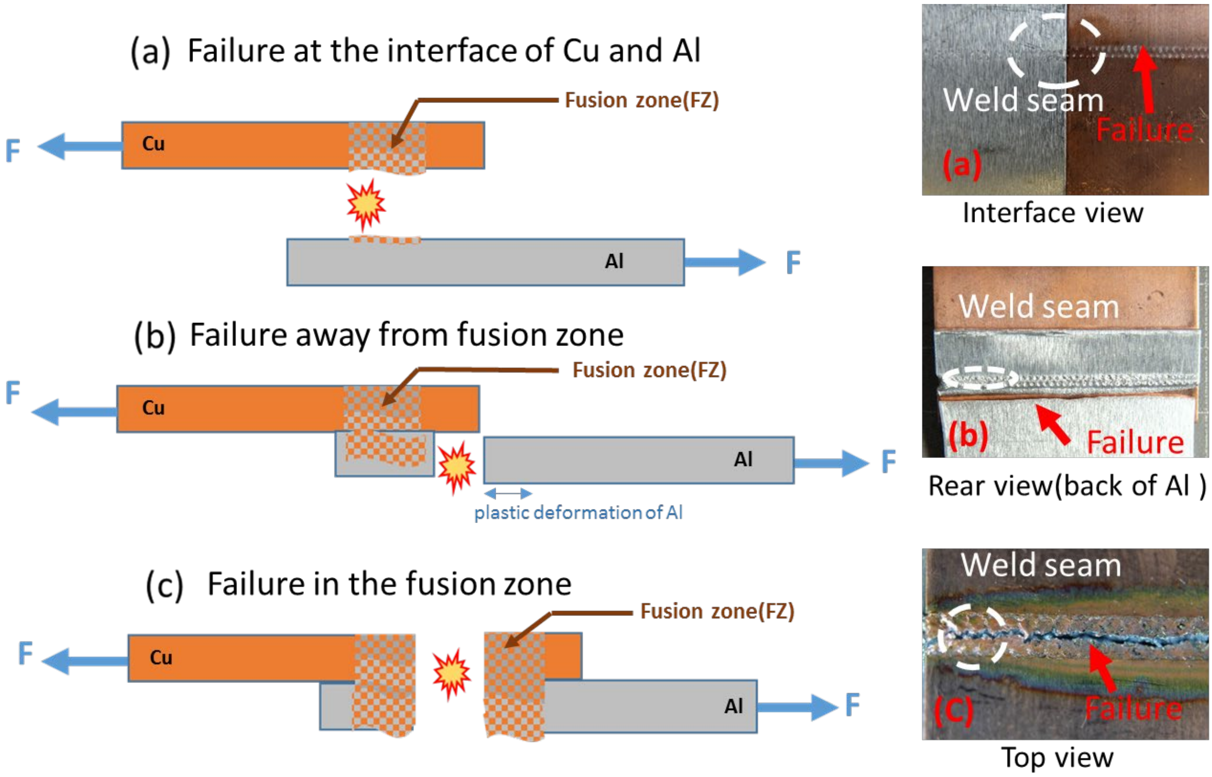

Fig. 6. Schematic of Cu-Al after failure (a) failure at the interface of Cu-Al (b) failure at the Al side (HAZ) (c) failure at fusion zone

drawn for case (a), rear view i.e. bottom of aluminum sheet is shown for case (b) and top view is shown for case (c) in the Fig 6.

The weld seam development in Fig 6 (a) is very thin and the entire seam undergoes resistance to the shear force. The crack propagation is along the interface in the laser scan direction of the weld seam. The cross-section is separated at the interface (horizontal) of Cu-Al as shown in (a). In this condition, the plastic deformation of the joint system is very low and characterized as the brittle failure. The failure of the joint system in case (a) is at the interface. In case (b), the seam is well developed and is a combination of ductile rich and brittle rich IMC as discussed in the microstructural section 3.3. In this condition, the material undergoes a large plastic deformation on the Al side largely involving base or heat affected zone of Al. The location of the failure is away from the fusion zone (Fig 7 (a)) or is in the heat affected zone of Al material. However further investigation are required to understand the region. It is clear from the fractures that the aluminum metal is the limiting partner considering the base metal strengths of the aluminum in contrast to copper.

The plastic deformation on the Al side and the final fracture region shown in Fig 7(c).The final fracture of the aluminum is approximately, 1300-1400 μm away from the edge of fusion zone. The shear off angle at the final fracture is approximately 14°~15°.

In condition (c) for failure at the fusion zone, the material separation is in the vertical direction of the weld running along the laser scan length of the fusion zone. The failure is initiated at the edge of the fusion zone on aluminum side and propagates in the length direction involving either fusion zone edge (Fig 7(b)) or HAZ Al. In this condition, the amount plastic deformation of the joint system is low as compared to condition (b).The failure location in this condition is at the intermetallic structure. For the Fig 8(b) the intermetallic phase is $CuAl_2$ dendritic structure. However, the failure is not attributed to any particular phase or structure since this was not included in the scope of this study.

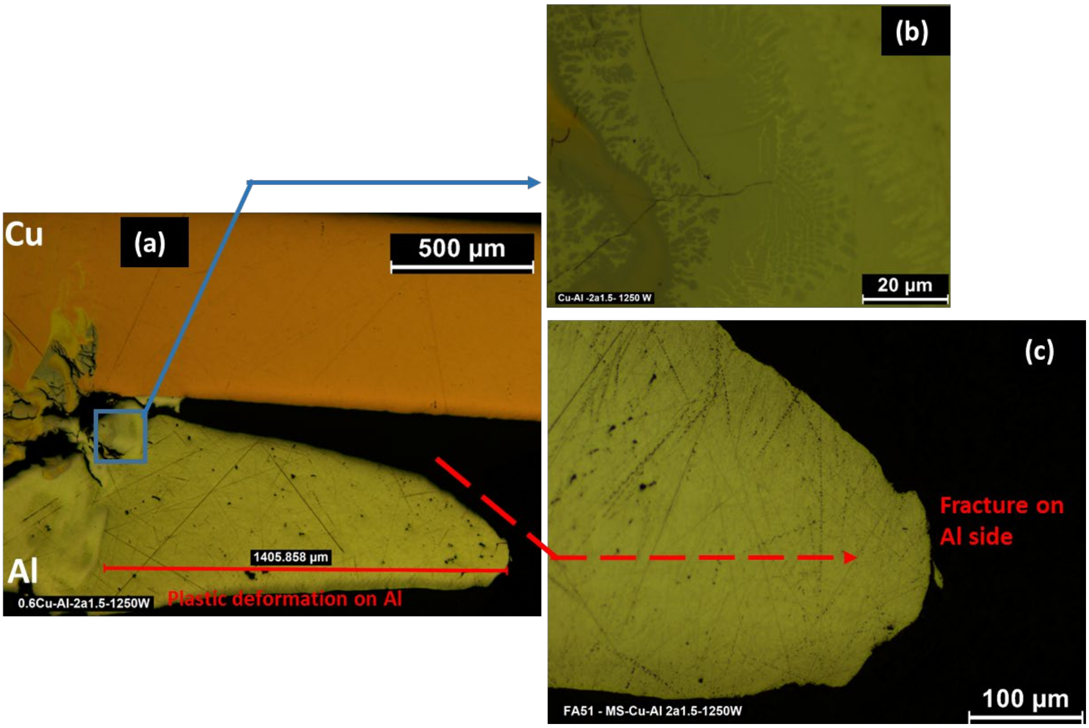

Fig. 7. (a) Failure at the Al material side despite the presence of (b) intermetallic structures at the weld seam and (c) large plastic deformation of the material

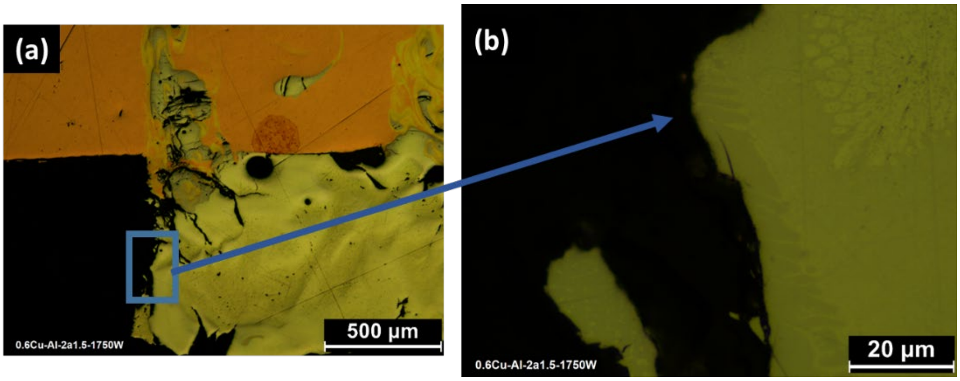

Fig. 8. (a) Fusion zone failure with separation of Al in vertical direction and (b) showing the failure is at the Intermetallic structure

4. Conclusion

In laser joining of Cu-Al, the intermixing is rapid because of the difference in density and melting temperatures of the joining partners. From the cross-sectional analysis and tensile shear test, it is evident that for the Cu-Al system the maximum shear strength is achieved at significant level of intermixing and evident presence of large complex intermetallic structures in seam. However, they are distributed all over the fusion zone rather than concentrated at the interface. Using a beam oscillation in form of infinite shape, a discontinuous seam in cross-sectional direction is formed which is a combination of different degree of intermixing. Hence, a combination of ductile and brittle intermetallic microstructure is formed which results in a strong joint involving large plastic deformation on the Al sheet.

Joint failure is classified based on the fracture location. It is shown that the joint fails away from the fusion zone despite the presence of brittle intermetallic structures in the weldment. A large plastic deformation of the aluminum sheet after failure shows the ductile behavior of the joint system. However further investigation on this region is necessary to understand the grain texture near the fusion zone on the aluminum side. In conclusion, this paper shows that using a beam oscillation in Cu-Al joining a combination of brittle and ductile intermetallic regions can make the joint stronger and contribute to a plastic deformation of the joint system and the final fracture shifted to the Al material away from complex intermetallic phases.

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