

Article

# Welding of Copper to Aluminium with laser beam wavelength of 515 nm

Karthik Mathivanan <sup>1,†,‡</sup> , Peter Plapper <sup>1,‡</sup>

<sup>1</sup> Faculty of Science, Technology and Medicine, University of Luxembourg, 6 Rue Richard Coudenhove-Kalergi, L-1359 Luxembourg, Luxembourg; karthik.mathivanan@uni.lu

\* Correspondence: karthik.mathivanan@uni.lu; Tel.: +352-466-644-5382

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**Abstract:** In laser joining of copper (Cu) and aluminum (Al) sheets, the Al sheet is widely chosen as the top surface for laser irradiation because of increased absorption of laser beam and lower melting temperature of Al in contrast to Cu. This research focus on welding from Cu side to Al sheet. The main objective of irradiating the laser beam from the copper side (Cu on top) is to exploit higher solubility of Al in Cu. A significantly lower laser power can be used with 515 nm laser in comparison to 1030 nm. In addition to low laser power, a stable welding is obtained with 515 nm. Because of this advantage, 515 nm is selected for the current research. By fusion of Cu and Al the two sheet metals are welded, with presence of beneficial Cu solid solution phase and Al+Al<sub>2</sub>Cu in the joint with the brittle phases intermixed between the ductile phase. Therefore the mixed composition strengthens the joint. However excessive mixing leads to formation of more detrimental phases and less ductile phases. Therefore optimum mixing must be maintained. Energy dispersive X-ray spectroscopy (EDS) analysis indicate that large amount of beneficial Cu solid solution and Al rich phases is formed in the strong joint. From the tensile shear test for a strong joint, fracture is obtained on the heat-affected zone (HAZ) of Al. Therefore the key for welding from copper side is to have optimum melt with beneficial phases like Cu and Al+ Al<sub>2</sub>Cu and the detrimental phases intermixed between the ductile phases

**Keywords:** Laser welding; Cu-Al welding; green laser; Micro-structure analysis; Energy dispersive X-ray spectroscopy (EDS)

## 1. Introduction

Laser welding of copper to aluminum sheet is challenging because of the poor absorption of laser radiation by these materials. Al sheet is widely selected as the top material to irradiate by the laser beam because of its relatively high absorption to laser radiation (1030 nm) and low melting point (660 ° C) in comparison to Cu. To obtain a good joint with Al to Cu is to irradiate laser from Aluminum (Al) to control the weld depth and mixing of Cu in Al [1,2].

Irradiation of laser beam onto Al (660 ° C) allows for braze welding of Al to Cu. This approach is useful for this combination because the detrimental intermetallic phases formed can be reduced [3,4]. Larger weld seam can be obtained with laser beam oscillation, by maintaining keyhole conditions (10<sup>7</sup> W/cm<sup>2</sup>) required to weld highly reflective metals like Al and Cu [5]. Oscillated laser beam is beneficial in controlling the depth of penetration into the bottom sheet [6,7]. Welding from Cu sheet is challenging in terms of higher reflectivity, thermal conductivity and melting temperature (1080 ° C) in contrast to Al. Therefore, to weld from copper side high intensity or good absorption of laser light is a fundamental requirement [8–10]. Very less investigations are conducted in the analysis of welding from Cu to Al [7,11,12]. The phase composition and the intermixing of Cu and Al in Cu-Al (Cu on top) configuration is not well studied.

This paper investigates welding of Cu-Al (Cu on top) with green laser wavelength of 515 nm. Welding of Cu with green laser wavelength improves the absorption of laser light and increases the process stability [9,10,13], in comparison to near-IR laser wavelength of 1030 nm. This paper exploits the higher solubility of Al in Cu, which is about 18.5



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at.%. With this, a higher amount of Al can be intermixed to Cu during welding process. Therefore, a higher depth of penetration and mixing of Cu and Al is feasible. The purpose of this paper is to investigate and show that a strong joint based on fusion welding of Cu to Al can be achieved with laser beam.

The remainder of the paper is structured as follows. The laser equipment, oscillation strategy and microscope used are detailed in Materials and Methods section 2. The results are discussed in subsections starting from the benefit of using green laser wavelength of 515 nm in comparison to 1030 nm (section 3.1), the tensile shear test (section 3.2) and micro-structural analysis (section 3.3) is presented. Finally, conclusion is discussed in section 4.

## 2. Materials and Methods

### 2.1. Material

For laser welding experiment, thin copper (Oxide free- OF 99.95% pure) and aluminum (Al 1050) sheets each of thickness 0.4 mm is used with the dimensions mentioned in Table 1.

Table 1: Details of the materials used for laser welding

Material	Grade	Dimension [mm <sup>3</sup> ]
Copper	Cu-OF	0.4 x 40 x 50
Aluminium	1050 Al	0.4 x 40 x 50

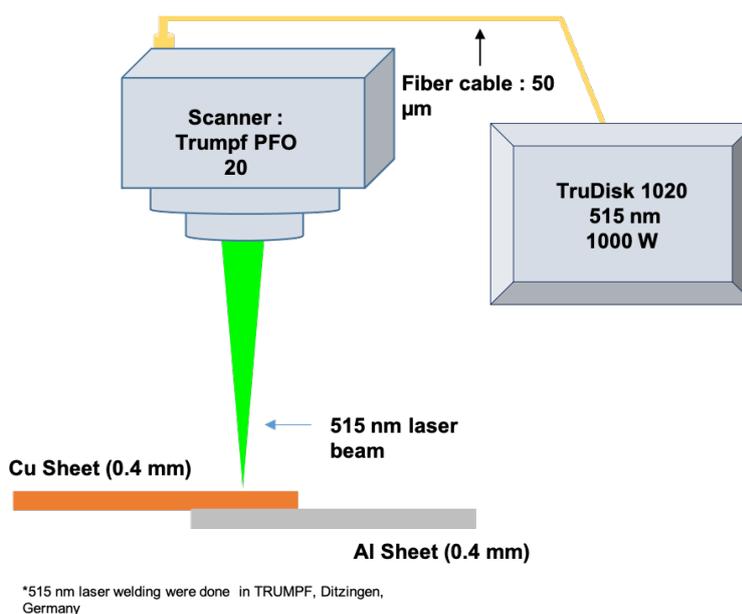


Figure 1. Schematic of welding process for Al and Cu with green laser wavelength of 515 nm

Laser welding experiment for green laser wavelength of 515 nm was performed in TRUMPF (Ditzingen, Germany) with maximum power of 1000 W disk laser in overlap configuration with copper placed on top of Aluminum as shown in figure 1. The benefit of using a green laser for Cu-Al welding is shown by comparing it with 1030 nm laser with a maximum power of 2000 W (1030 nm laser in section 3.1). The scanning optics for both the laser systems, 1030 nm and 515 nm, are from TRUMPF with a minimum spot diameter of 89 μm.

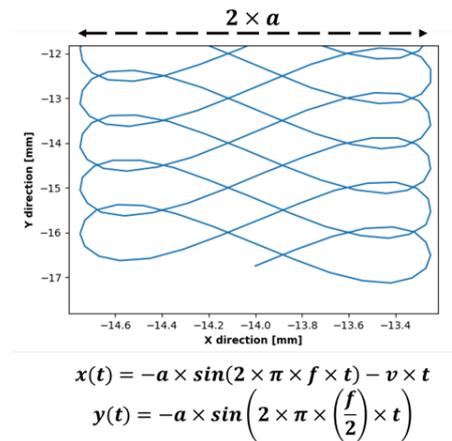
### 2.2. Beam Oscillation

The laser welding was performed with wobbling in order to enlarge the seam width, as the beam diameter used is 89 μm. Laser beam oscillation in form of infinite shape with

Laser wavelength	Focal spot diameter	Section
1030 nm	89 $\mu\text{m}$	Section 3.1
515 nm	89 $\mu\text{m}$	Section 3.1-3.3

Table 2: Laser welding system for Cu-Al joints

amplitude (a) 0.75 mm ( $2a=1.5$ ), frequency (f) of 100 Hz and the velocity (v) of 50 mm/s. The oscillatory motion in X and Y coordinates is defined as shown in figure 2. The laser power for investigation is in the range of 650 W to 900 W for green laser (515 nm) and 900 W to 1000 W for IR laser (1030 nm).



**Figure 2.** Trajectory of laser beam with, a as amplitude in mm, f is the frequency in Hz, v is the feed velocity in mm/s.

### 2.3. Microstructural Characterization

The microstructural analysis is performed using optical microscope (Leica DM 4000 M) and Scanning Electron microscope combined with EDS (Energy dispersive X-ray spectroscopy with Apollo XV detector) for composition of elements in atomic % in the joint. For microstructural analysis, the joint cross-section is prepared by sectioning and moulding in the resin followed by grinding and polishing procedure to obtain a mirror polished surface. The moulding, grinding and polishing procedures are followed as outlined by [14].

### 2.4. Tensile shear test

The tensile shear test is carried out with Zwick Z010 machine at room temperature (25°C). The feed rate of crosshead is 1.2 mm/min [5]. The tensile shear strength of the materials are reported in terms of N/mm<sup>2</sup>.

## 3. Result and discussion

### 3.1. Laser absorption issue for welding Cu-Al with 1030 nm in comparison to 515 nm laser

cu-al green-IR-unstablewelds.png

**Figure 3.** Top view of Cu-Al welded with green laser (515 nm) and IR laser (1030 nm)

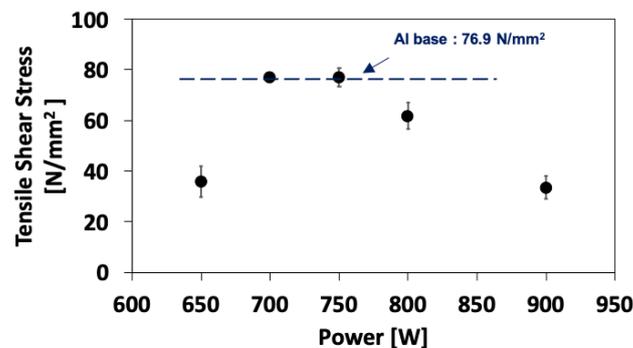
In this section, the necessity of welding with green laser wavelength at 515 nm for Cu and Al is studied. For this reason, comparison of weld beads of Near IR laser wavelength (1030 nm) and green laser wavelength (515 nm) in continuous wave mode is performed. The experiment is conducted with the laser wavelengths of 515 nm and 1030 nm, using same optical parameters, resulting in focal spot diameter of 89  $\mu\text{m}$ . The wobbling trajectory for both the laser wavelengths is fixed to wobbling speed of 50 mm/s, wobble width of 1.5 mm, wobble frequency of 100 Hz and thickness of Cu and Al is 0.4 mm each. Therefore,

all the parameters are fixed and weld bead formation for green laser (515 nm) and Near IR laser (1030 nm) wavelength is compared for stability of bead formation. The figure 3 shows the bead on top of Cu sheet, welded with Al for green laser wavelength of 515 nm and near-infrared laser wavelength of 1030 nm.

The first difference is the power required to perform welding of copper and aluminium. For 515 nm, with improved absorption of the laser radiation, a weld is achieved with a minimum power of 650 W. The formed weld bead is stable and consistent with the trajectory of oscillation imprinted on the material. This in comparison to 1030 nm, higher power of 900 W is required. However, the bead suffers from inconsistency over the length direction (figure 3). For 1030 nm (figure 3 marked in red box), the bead formed at low laser power is unstable, which is due to the poor absorption of Cu at 1030 nm. For 515 nm laser, the development of weld bead and intermixing is stable, and a good weld bead is obtained for a laser power of 700- 750 W. This is the optimum melt condition and detailed analysis of this case is presented in section 3.2. From this condition, increasing the laser power promotes excessive inter-diffusion of Al and Cu. as shown in figure 3 for 515 nm at power 900 W. On the other hand for 1030 nm laser, good weld bead is obtained at laser power of 950 W and at 1000 W excessive Al and Cu is melted resulting is an over-weld. Therefore, with green laser a stable weld bead is obtained with low laser power, which is very important for welding Cu in dissimilar combination to Al. For this reason, in this research, the green laser is required for the study of welding from Cu to Al sheet. Detailed results of welding Cu-Al with the green laser is explained in the following sections 3.2 and 3.3

### 3.2. Tensile shear test

The weld strength is evaluated by tensile shear test with five sample per test ( $n=5$ ). The relation of laser power to the tensile shear stress ( $\text{N}/\text{mm}^2$ ) is shown in figure 4 and a schematic of the Cu-Al weld failure location, and the corresponding cross-section view of the failure after metallography is shown in figure 5.

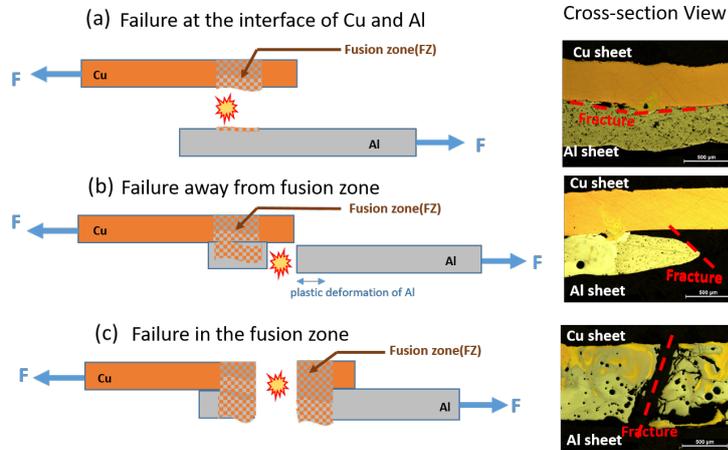


**Figure 4.** Tensile Shear force of Cu-Al joints (copper on top) welded with 515 nm laser wavelength for different powers [W]

For a power of less than 650 W, no joint between Cu and Al is obtained. At 650 W, average tensile shear strength of  $35.9 \text{ N}/\text{mm}^2$  is obtained, with a deviation of  $6 \text{ N}/\text{mm}^2$ . The weld failure in this case occurs at the joint interface, as shown in figure 5 (a). Increasing the power to 700 W and 750 W, shear force increases significantly and achieve maximum strength of base Al ( $76.9 \text{ N}/\text{mm}^2$ ) with a small standard deviation of  $0.78 \text{ N}/\text{mm}^2$ . Further, increasing the power to 800 W, shear force decreases to a mean value of  $61.81 \text{ N}/\text{mm}^2$ . At 900 W, a large amount of inter-diffusion is promoted and there is a significant reduction in the shear strength to a value of  $33.5 \text{ N}/\text{mm}^2$ .

As a result of tensile shear test three different failure modes were observed i.e. (a) Interface, (b) Al HAZ (Heat Affected Zone), (c) fusion zone. For low laser power of 650 W the joint is weak, and it fails at the interface of Cu and Al (figure 5, case (a)). For increased power of 700 W and 750 W, the weld is strong, and the failure is on the heat affected zone (HAZ) of Al. Large plastic deformation of Al and failure away from the fusion zone (figure

5, case (b)) were obtained, which represents a good joint. For increased laser power (900 W) excessive penetration results in formation of over-mixing of Cu and Al and results in a joint with large amount of intermetallic phases. In this condition, the joint fails in the fusion zone (figure 5, case (c)).

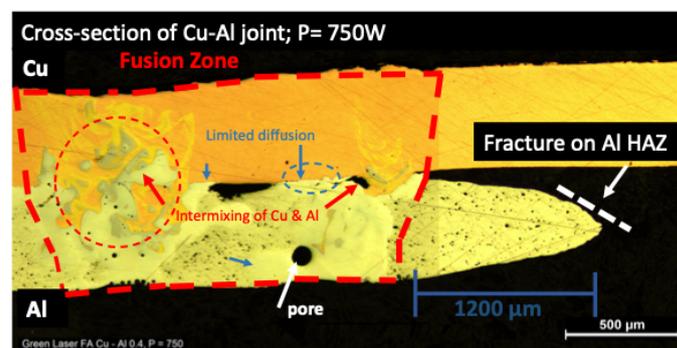


**Figure 5.** Cross-sectional view of Cu-Al joint with schematic and micrograph showing the failure location after tensile shear test

In conclusion, from tensile shear test, strong joint is obtained for case (b), despite intermixing of Cu and Al. A large depth into the bottom sheet (Al) is achieved. More detailed microstructural analysis and the elemental composition of the Al and Cu intermixing in fusion zone responsible for the strong joint is explained in section 3.3.

### 3.3. Microstructural analysis

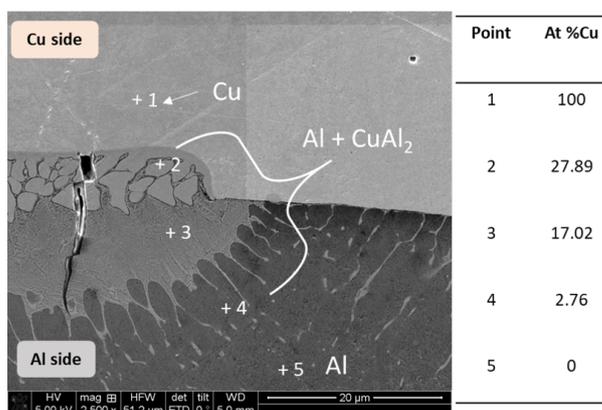
The microstructural analysis is performed for the strong weld to understand the morphology and composition of Cu and Al in the joint that contribute to the weld strength. The weld joint at laser power of 750 W in case b (figure 5), the weld is strong and the intermixing of Cu and Al is present as shown in the cross-section view in figure 6. For Al-Cu system the possible phases formed in the joint are Al solid solution, Al+Al<sub>2</sub>Cu, Cu, AlCu, Al<sub>3</sub>Cu<sub>4</sub>, Al<sub>4</sub>Cu<sub>9</sub> and Cu solid solution. The Al, Cu solid solution phases, Al+Al<sub>2</sub>Cu phases are beneficial and the phases such as AlCu, Al<sub>3</sub>Cu<sub>4</sub>, Al<sub>4</sub>Cu<sub>9</sub> are detrimental intermetallic phases.



**Figure 6.** Optical microscope image of the strong joint, showing fusion zone with intermixed zone and limited diffusion zone

The application of laser energy activates the melting of Cu and Al, as a result the Cu from the top sheet diffuses into the Al sheet (bottom) and the Al diffuses into the Cu sheet (top). This leads to intermixing of the metals Cu and Al. The diffusion of the metals result in formation of complex intermixing across the Cu-Al sheet interface. Two distinct regions are formed, one with high intermixing (red arrow in figure 6) and another

with limited inter-diffusion (Blue arrow in figure 6). In the intermixed region and limited diffusion zone, interface is bonded metallurgically with a mix of chemical composition. The bonding is based on diffusion of Cu and Al in molten state. Detailed analysis of Al and Cu composition in these regions indicate that large amount of Cu solid solution phases are present, and the intermetallic compounds are thin and intermixed between beneficial Cu rich (> 80 at % of Cu) and Al rich phases. Energy Dispersive X-Ray Spectroscopy (EDS) is used to measure elemental composition of Cu and Al in the high intermixing and limited intermixing regions. The SEM (scanning electron microscope) image of the limited diffusion zone and the EDS measurement of Al composition (At %) is shown in 7. From the EDS analysis, Al+Al<sub>2</sub>Cu phase is mainly formed in the limited intermixed zone. The point 1 in figure 7 is Cu and point 2, 3 is Al+Al<sub>2</sub>Cu phase. The phase in point 2 is based on hypo-eutectic reaction. The point 3 is eutectic phase and point 4 is Al solid solution. All these phases are not detrimental intermetallic phases. The structure of the phase 3 at eutectic composition is Lamellar, which consist of many thin alternating layers. This phase is good for promoting both the strength and ductility of the joint. This region is mainly Al rich, which indicates metallurgical bonding based on the eutectic reaction. The diffusion in this region is mainly due to the heat conducted from highly intermixed zone. In the limited diffusion zone, formation of detrimental intermetallic phases are minimum or avoided.



**Figure 7.** EDS analysis of microstructures in the limited diffusion zone

The SEM image in figure 9 shows the magnified view of the intermixed zone. For the intermixed zone, EDS line scan is performed in the Al region to understand the mixing of Al and Cu, as shown in (figure 8). The result of the line scan is plotted in (figure 9) with the distance in x-axis and the at % of Cu in y-axis. The intermixed zone is found to be a combination of ductile and brittle phases. The mixing of Cu in the range of 50- 80 at% result in detrimental phases such as AlCu, Al<sub>3</sub>Cu<sub>4</sub>, Al<sub>4</sub>Cu<sub>9</sub>. In the intermixed zone, more than 70 % of the inter-diffusion results in formation of the Cu rich solid solution (80-100 at% Cu) and Al+Al<sub>2</sub>Cu phase which is not of detrimental intermetallic composition. The presence of Cu solid solution phase and the Al+Al<sub>2</sub>Cu phase is beneficial for joint ductility. The light contrast region (white color in figure 10), from EDS analysis, is Cu solid solution (90 % at). Because of the intermixing, local interfaces are formed (orange dashed lines in figure 10) as the less dense Al floats to the top side (Cu sheet) of the weld seam and meet with the sinking copper.

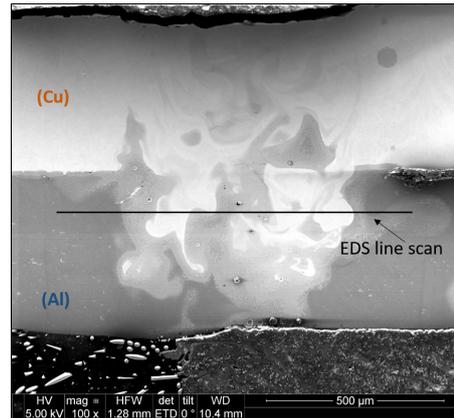


Figure 8. Scanning electron microscopic image of the intermixed zone

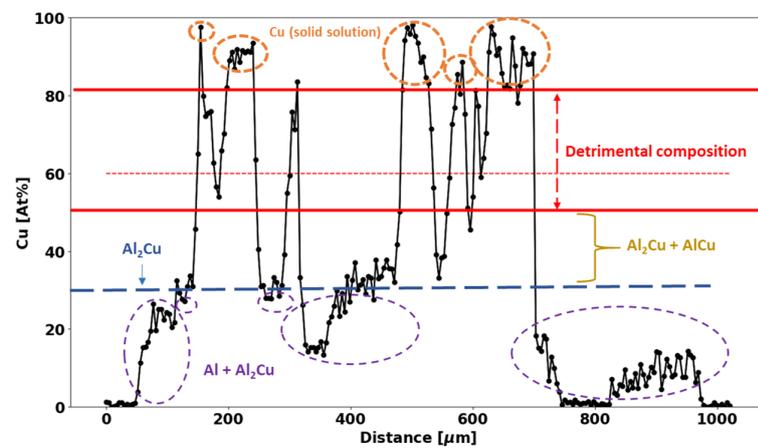


Figure 9. Plot of Cu and Al in at % on the Al side of the intermixed zone

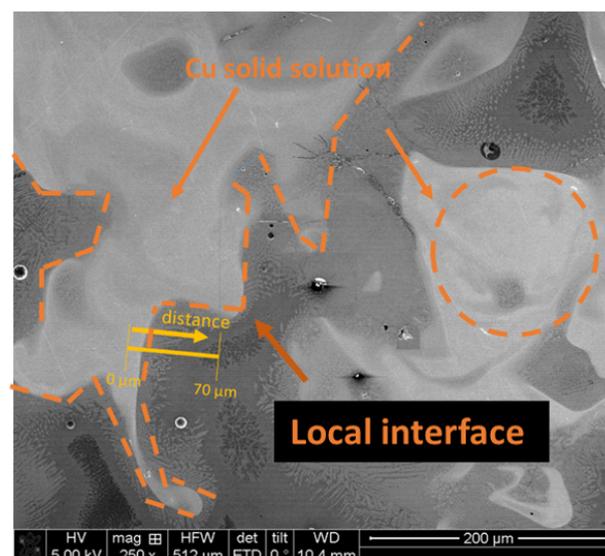
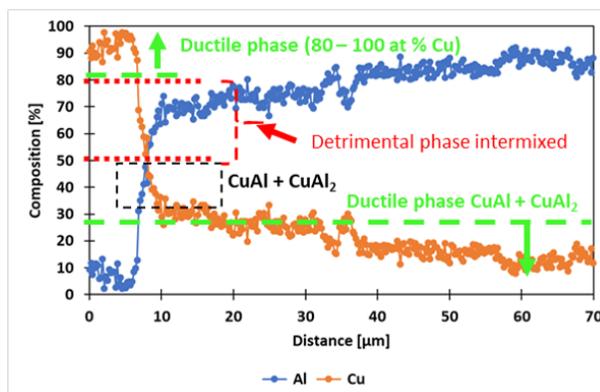


Figure 10. Composition analysis of intermixed zone performed for 70  $\mu\text{m}$  (yellow line) starting from Cu rich to Al rich zone



**Figure 11.** Diffusion plot in atomic %, of the local interface in the intermixed zone starting from the Cu solid solution ( $0\mu\text{m}$ ) yellow line in SEM image (figure 10) for  $70\mu\text{m}$

To investigate the diffusion at the local interface, region marked in yellow line for a distance of  $70\mu\text{m}$  in figure 10 is selected. The EDS points are collected for  $70\mu\text{m}$  with a step size of  $0.23\mu\text{m}$ . The figure 11 shows the plot of Al and Cu composition (in at %) in Y-axis and the scan distance for EDS in X-axis. The first few microns of about  $9\mu\text{m}$  is Cu solid solution. The transition from the Cu solid solution to the  $\text{Al}_2\text{Cu}$  is the detrimental intermetallic phases (50- 80 at%) such as  $\text{AlCu}$ ,  $\text{Al}_3\text{Cu}_4$ ,  $\text{Al}_4\text{Cu}_9$ . The highly detrimental composition is in the range of 70-55 at. % of Cu and the transition is very quick and is thin layered of about  $4\text{-}5\mu\text{m}$ . The next phase is  $\text{Al}_2\text{Cu}$  which is surrounded by  $\text{Al} + \text{Al}_2\text{Cu}$  phase based on hyper and hypo eutectic reaction. Because of activating the intermixing from copper, more ductile phase such as Cu solid solution and Al rich dendrite is formed at the interface. A combined presence of ductile and brittle phase increases the strength of the joint.

#### 4. Conclusion

Laser welding with green wavelength of  $515\text{ nm}$  is studied to join Cu to Al with Cu placed on top of Al. With green laser wavelength of  $515\text{ nm}$ , the welding of Cu to Al is achieved with a low laser power of  $700\text{-}750\text{ W}$  with stable weld bead formation. Welding with Cu on top and Al in bottom configuration allowed for a larger intermixing of Al into Cu, with formation of more beneficial phases like Al solid solution, Cu solid solution and  $\text{Al} + \text{Al}_2\text{Cu}$ . With this approach, a strong joint with failure on the HAZ of Al is obtained with high depth of penetration and significant intermixing. Despite large Al and Cu melt involved in the joint, thickness of the detrimental intermetallic phase in the local interface is small (about  $4\text{-}5\mu\text{m}$ ). The detrimental phases are intermixed in between the ductile phase compositions, i.e. Al rich and Cu solid solution. With this paper, fusion welding approach for joining Cu and Al system is demonstrated with a strong joint.

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**Conflicts of Interest:** The authors declare no conflict of interest

#### Abbreviations

The following abbreviations are used in this manuscript:

HAZ	Heat-affected zone
EDS	Energy-dispersive X-ray spectroscopy
SEM	Scanning Electron Microscope
Al	Aluminium
Cu	Copper

## References

1. Solchenbach, T.; Plapper, P. Mechanical characteristics of laser braze-welded aluminium-copper connections. *Optics and Laser Technology* **2013**, *54*, 249–256. doi:10.1016/j.optlastec.2013.06.003.
2. Shin, W.S.; Cho, D.W.; Jung, D.; Kang, H.; Kim, J.O.; Kim, Y.J.; Park, C. Investigation on Laser Welding of Al Ribbon to Cu Sheet: Weldability, Microstructure, and Mechanical and Electrical Properties. *Metals* **2021**, *11*. doi:10.3390/met11050831.
3. Schmalen, P.; Plapper, P. Evaluation of laser braze-welded dissimilar Al-Cu joints. *Physics Procedia* **2016**, *83*, 506–514. doi:10.1016/j.phpro.2016.08.052.
4. Zhou, L.; Li, Z.Y.; Song, X.G.; Tan, C.W.; He, Z.Z.; Huang, Y.X.; Feng, J.C. Influence of laser offset on laser welding-brazing of Al/brass dissimilar alloys. *Journal of Alloys and Compounds* **2017**, *717*, 78–92. doi:10.1016/j.jallcom.2017.05.099.
5. Mathivanan, K.; Plapper, P. Laser overlap joining from copper to aluminum and analysis of failure zone. Conference proceeding of Lasers in Manufacturing (LiM), 2019, pp. 1–11.
6. Fetzer, F.; Jarwitz, M.; Stritt, P.; Weber, R.; Graf, T. Fine-tuned remote laser welding of aluminum to copper with local beam oscillation. *Physics Procedia* **2016**, *83*, 455–462. doi:10.1016/j.phpro.2016.08.047.
7. Mathivanan, K.; Plapper, P. Laser welding of dissimilar copper and aluminum sheets by shaping the laser pulses. *Procedia Manufacturing* **2019**, *36*, 154–162. doi:10.1016/j.promfg.2019.08.021.
8. Heider, A.; Stritt, P.; Hess, A.; Weber, R.; Graf, T. Process stabilization at welding copper by laser power modulation. *Physics Procedia* **2011**, *12*, 81–87. doi:10.1016/j.phpro.2011.03.011.
9. Alter, L.; Heider, A.; Bergmann, J.P. Investigations on copper welding using a frequency-doubled disk laser and high welding speeds. *Procedia CIRP* **2018**, *74*, 12–16. doi:10.1016/j.procir.2018.08.003.
10. Engler, S.; Ramsayer, R.; Poprawe, R. Process studies on laser welding of copper with brilliant green and infrared lasers. *Physics Procedia* **2011**, *12*, 342–349. doi:10.1016/j.phpro.2011.03.142.
11. Lee, S.J.; Nakamura, H.; Kawahito, Y.; Katayama, S. Effect of welding speed on microstructural and mechanical properties of laser lap weld joints in dissimilar Al and Cu sheets. *Science and Technology of Welding and Joining* **2014**, *19*, 111–118. doi:10.1179/1362171813Y.0000000168.
12. Fortunato, A.; Ascari, A. Laser Welding of Thin Copper and Aluminum Sheets: Feasibility and Challenges in Continuous-Wave Welding of Dissimilar Metals. *Lasers in Manufacturing and Materials Processing* **2019**, *6*, 136–157. doi:10.1007/s40516-019-00085-z.
13. Stritt, P.; Hagenlocher, C.; Kizler, C.; Weber, R.; Rüttimann, C.; Graf, T. Laser spot welding of copper-aluminum joints using a pulsed dual wavelength laser at 532 and 1064 nm. *Physics Procedia* **2014**, *56*, 759–767. doi:10.1016/j.phpro.2014.08.083.
14. Schmalen, P.; Mathivanan, K.; Plapper, P. Metallographic Studies of Dissimilar Al-Cu Laser-Welded Joints Using Various Etchants. *Metallography, Microstructure, and Analysis* **2018**. doi:https://doi.org/10.1007/s13632-018-0501-y.