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Intermediate layer characterization and fracture behavior of laser-welded copper/aluminum metal joints

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Copper and aluminum were welded using a continuous Nd:YAG laser, and the influence of the processing parameters on the intermediate layer was investigated. The intermediate layer along the interface was characterized, and the failure mechanism was identified. Four distinct zones with various intermetallic compounds and structures formed in the intermediate layer and determined the corresponding joint strength. Utilizing gradually increasing heat input produced different thicknesses for these four zones. A laser beam power of 1650 W and a welding speed of 95 mm/s were the optimized parameters. The thickness of the intermetallic compound γ_2-Cu_9Al_4 and the shear–tensile strength of the joint decreased with the increase of welding speed in the weld. The shear–tensile load of the dissimilar metal joint reached 539.52 N with the optimized parameters. Fracture during shear–tensile testing occurred in the zone with 20.08–54.65% Cu. It was concluded that eutectic and hypoeutectic structures containing a significant amount of θ-$CuAl_2$ led to a weak joint. The relationship between the mechanical properties and thickness of the different intermediate zones is thoroughly illustrated.

1. Introduction

Dissimilar metal joints of thin components are often inevitable in microelectronics and alternative energy devices in particular, as well as in batteries for hybrid vehicles and fuel cells [1]. Using these joints significantly increases the flexibility in engineering design and production processes. Also, the electrical, mechanical, thermal, and corrosion resistance properties of such materials may benefit from different combinations of metals [2,3]. Therefore, a sound joining technique of dissimilar materials is indispensable. However, due to the differences in chemical, physical, and thermal properties, poor solubility is normally reflected on the microstructure of the joint produced, and problems such as tendency to crack and the appearance of brittle intermetallic compounds (IMCs) will significantly decrease the mechanical properties [1].

Various joining techniques have been applied to joints of dissimilar forms. However, conventional welding methods are limited for the following reasons: lack of precise control in heat input, low flexibility and repeatability, the need for contact between the welding equipment and the workpieces, and energy-focusing problems [3,4]. In the past decade, much attention has been directed towards laser beam welding (LBW). LBW overcomes the previously mentioned problems and has been successfully applied to a wide range of materials [5–8]. Its high energy density makes it possible to melt dissimilar metals with different thermal conductivities, and the low heat input results in higher rates of heating and cooling, which translates into its unique advantages in the welding of dissimilar metals [9].

Cu–Al joints, which are known as high reflective metals (HRM), constitute the subject of this investigation [10]. Various joining methods have been used on this combination, such as explosive welding, friction welding, and brazing [11–13]. These two metals are soluble in each other in the liquid state, but during the solidification process, brittle IMC phases usually form on the transition layers, which definitely harm the mechanical properties of the joints. Many researchers have focused on the formation and characterization of IMCs at the interface and their relationship to the joint properties. Some studies have pointed out that increasing the amount of aluminum in the weld zone and efficient allocation of the laser beam power on both metals can optimize the microstructure of the intermediate layers and enhance the mechanical properties of the joints [14]. Braunovic et al. found that the contact resistance of Al–Cu joints increases linearly with the thickness of the intermetallics [15]. Xue et al. pointed out that a continuous and uniform IMC layer consisting of Al_2Cu and Al_4Cu_9 with a thickness of about 1 μm can be produced by friction stir welding (FSW), which is the main reason for its excellent metallurgical bonding

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[12]. Lee et al. studied the IMC layer that formed after the FSW joints were annealed. AlCu and Al_2Cu were found to form a thick IMC layer that could seriously decrease the tensile strength [16]. Hang et al. found that Cu_9Al_4 and $CuAl_2$ were the main IMC products in Cu ball bonds during isothermal aging [17], and investigations have been done for laser welding of copper and aluminum using filler materials. Pure metal foils such as silver, nickel, and tin and alloys such as $CuSi_3$, $AlSi_2$, and Sn–Ag–Ti can improve the mechanical properties to some extent [1,18–20]. Studies carried out by Balu, Hailat, and Bird et al. have explained the performance of Cu–Al joints from the perspective of process parameters or joint configuration, but no detailed study has been performed to explain the division of the transition layer into more elaborate zones, the characteristics of the transition region, crystal morphology, specific IMC categories, or the relationship of different zones with mechanical properties [1,21,22].

In this paper, continuous laser welding of aluminum and copper was investigated. The present study attempted to characterize the different zones in the transition layers of overlap joints based on the metallurgical structure, composition distribution, thickness, and their relationship with shear strength. The fracture morphology was also studied to determine which zone had a detrimental influence on mechanical properties.

2. Materials and experimental procedures

1060 aluminum alloy (100 × 20 × 0.3 mm) and T2 copper (100 × 20 × 0.3 mm) were welded with a JK2003SM Nd:YAG laser. The oxide film on the surface of each workpiece was removed by mechanical polishing with sand paper before laser welding. The spot diameter was 0.8 mm and the focal length of the lens was 300 mm. During welding, the welding speed was varied from 95 mm/s, 105 mm/s, 115 mm/s, 125 mm/s, 135 mm/s, and 145 mm/s to 155 mm/s in order to obtain different welding energy inputs per unit length while the laser power was fixed at 1650 W. To avoid back-reflection, the laser head was aligned so that the incident laser beam was inclined at 10° to the normal of the sample (Fig. 1). The copper part of the sample was placed on top of the aluminum part during welding. In all experiments, the specimens were tightly clamped due to the sensitivity of deformation to the clamping position and the laser focal position that is on the surface of the top plate.

Microstructures of the welded joints were observed by metallographic microscopy and scanning electron microscope (SEM) equipped with an energy dispersive X-ray spectrometer (EDS) for chemical constitution analysis. All weldments were etched using Keller's reagent (with a volume fraction of 1% HF, 1.5% HCl, 2.5% HNO_3, and 95% H_2O).

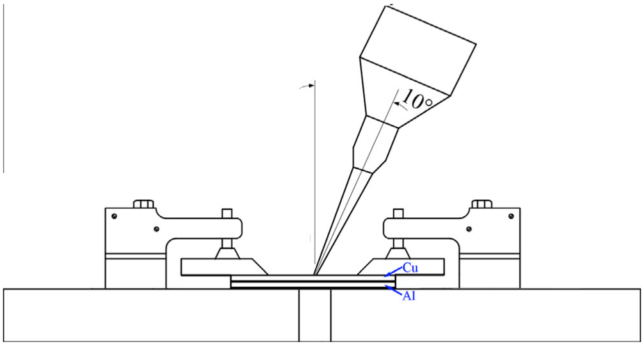

Fig. 1. Schematic of the welding jig and overlap joint used in the welding experiment.

The shear strength tests of the welds were conducted at room temperature to examine the effect of the intermetallic layers on the mechanical properties. Using the same processing parameters, three specimens were fabricated for the shear–tensile test, and then average values of the shear–tensile load were obtained.

After the shear strength tests, the fractography was examined by means of scanning electron microscopy (SEM) while an energy dispersive X-ray spectrometer was employed to carry out the composition distribution analysis.

3. Results and discussion

3.1. Microstructure and chemical composition of intermediate layer

In the case with a laser power of 1650 W and a welding speed of 95 mm/s, a metallographic picture of the Cu–Al overlap joint cross section is shown in Fig. 2, and an enlarged photo of the intermediate layer is shown in Fig. 3. A transition layer of upward convexity was formed between the Cu and Al base metals. This is because the expansion coefficient of Al is higher than that of Cu; thus, when heated by the laser, the melting Al expands more rapidly than the Cu. Molten Al in the center of the welding pool flowed upward, while the liquid at the edge of the welding pool flowed downwards. When cooling down, there is not enough time for melted metal to shrink back to its original shape, resulting in the formation of upward convexity. Because this type of weld creates a broad and shallow weld pool, and there is no extensive mixing of the two metals. This sample was a typical example of conduction-mode laser welding. A clear boundary divided these two metals, which is the focus of this study. Moreover, with the heat input into the weld pool reduced, the size of convexity decreased apparently.

The intermediate layer was made up of four zones, which could be distinguished by their morphology and colors. Data on the regional concentration range from the EDS results is shown in Table 1. During the solidification process, a partial solution formed via mechanical mixing and diffusion of aluminum and copper atoms in each other in the liquid state. Mechanical mixing may have resulted from convection inside the metals, stirred by expansion of the melting metals and shielding gas. Because the heating and cooling time was extremely short and the solute trapping occurred during the rapid solidification process, the interface and solution gradient were not subjected to violent fluctuations. Thus, the thickness and solute concentration of the four zones were maintained almost the same along the fusion line. In addition, due to the significant temperature and solute gradient of the

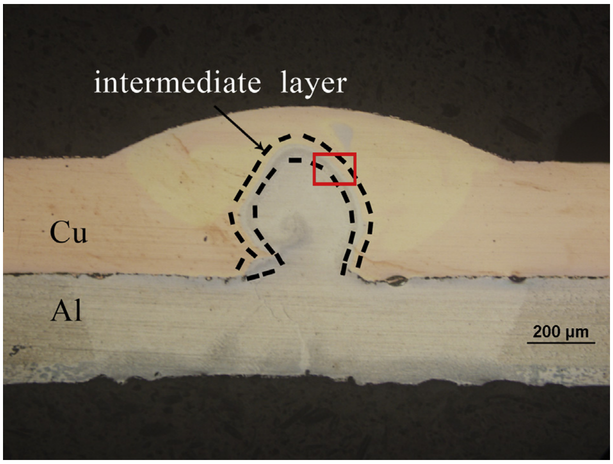

Fig. 2. Micrograph of weld joint cross section (laser beam power 1650 W, welding speed 95 mm/s).