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Laser welding of aluminum-copper joints using dynamic beam shape

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ABSTRACT: The paper presents a study on dissimilar laser welding of pure copper and Aluminum 3003 alloy. During this research conduction mode and keyhole mode were investigated. The microstructure of welded seams and the heat-affected zone were analyzed. Results demonstrated no mixing of metals and a significant presence of intercrystallite composites in the conduction mode. The use of a dynamic beam shape, characterized by two points with varying energy densities, resulted in uniform heat distribution at the copper-aluminum interface and high-strength joint. The tensile strength of the welded pipes ranged from 107-112 MPa, representing 75-80% of the base metal's strength. Additionally, the joints successfully passed a leak test at 43 atmospheres.

1 INTRODUCTION

Dissimilar metal (Al+Cu) joints can significantly increase the flexibility in engineering design and production processes. Also, the electrical, mechanical, thermal, and corrosion resistance properties of such materials may improve from different combinations of metals (Von, Blatter 1995). While copper possesses an excellent electric conductivity, its high density restricts the possibilities for lightweight designs. Furthermore, the comparatively high market price of copper leads to a cost increase for electronic constructions. This is the reason why it is intended to join copper with aluminum, which features similar electric properties at a reduced market price and a lower specific density for various industries, such as electronics, automotive, power systems.

2 CHALLENGES DURING AL – CU WELDING

Dissimilar metal joining of copper and aluminum is a well-known problem and has been the subject of investigations for decades. The main problem while joining this dissimilar combination is the formation of brittle intermetallic phases that degrade the electrical and mechanical properties of the joint. Very high intensity is required to join copper and aluminum sheets with a laser. The intermixture of copper and aluminum is vital for joint ductility. Besides, the laser welding of copper and aluminum poses multiple challenges including reflectivity, high thermal conductivity, and large differences in thermal expansion and melting points (Zhou et al. 2017). Another main challenge is the low absorption of aluminum and especially copper at the laser wavelength of 1 μm (Stritt et al. 2014). For laser welding, the spatial beam oscillation is effective in increasing the weld seam width and decreasing the depth (Fetzer et al. 2016). Controlling the depth of fusion in the Al-Cu system close to the interface is beneficial as mixing can be kept to a minimum (Shmallen et al. 2016). Welding with laser beam oscillation (or laser wobbling) when the laser beam is put in oscillation regarding to the molten puddle. Such oscillation, indicated as secondary motion, can occur with linear or curvilinear (circular, elliptic, or other) motion. This motion superimpose to the feeding motion of the laser beam along the welding path. Such oscillation technique becomes very promising especially when we refer to the use of fiber lasers, characterized by a higher quality of the laser beam that makes it more focusable on small sizes. Wobbling of the laser beam enlarges

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the beam/material interaction area and the weld width while decreasing the heat input required during welding (Wang et al. 2019). By wobbling the beam in highly reflective materials, such as copper, the local temperature of the material increases and so does its absorptivity. The dynamic movement of the laser can have different shapes and its controlled oscillation enables better temperature management during the process, which results in less steep heat, cooling rates, and thermal gradients. Thus, laser oscillation can improve the process by minimizing welding defects, without deleterious effects on the microstructure for Cu/Al dissimilar joints (Kraetzsch et al. 2011).

3 MATERIALS AND METHODS

The experiments were conducted using two pipes from pure copper and Al3003 alloy with thicknesses of 1 mm and diameters of 16 and 16.5 mm respectively. A copper tube was inserted into an aluminum tube and a laser beam welded the samples together, making an overlap joint (Figure 1). Prior to welding, the samples were cleaned by grinding with a wire brush and subsequently washed with acetone and ethanol to remove oxide films and grease. Argon with 99.99% of purity was used as a shielding gas to protect the welding zone, with a flow rate of 15 L/min. Obtained cross-sectional profiles during the welding were observed by an optical microscope. Tensile testing was performed according to the ISO 6892-1:2016.

In the experiments we used a high-power 14Kw fiber CW laser (Civan) with 1064 nm wavelength and dynamic beam shape feature. This technology allows dynamically tailor beam parameters to the required application. With the technology of CIVAN Optical Phase Array (OPA), multiple laser channels are electrooptically controlled to combine or interact with each other. For this study, a dynamic beam shape consisting of two points with different energies (Figure 1) was used. The laser machine and welding scheme is shown in Figure 1.

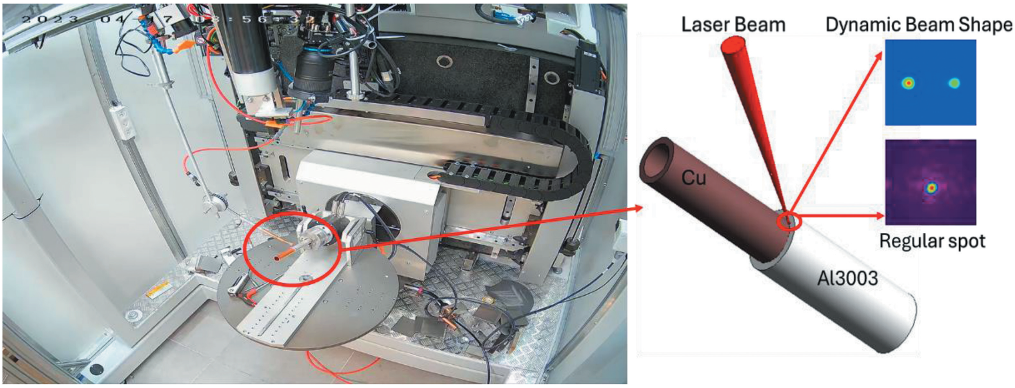


Figure 1. Welding cell, scheme of welding process, regular and dynamic beam shape (2 dots).

4 RESULTS AND DISCUSSION

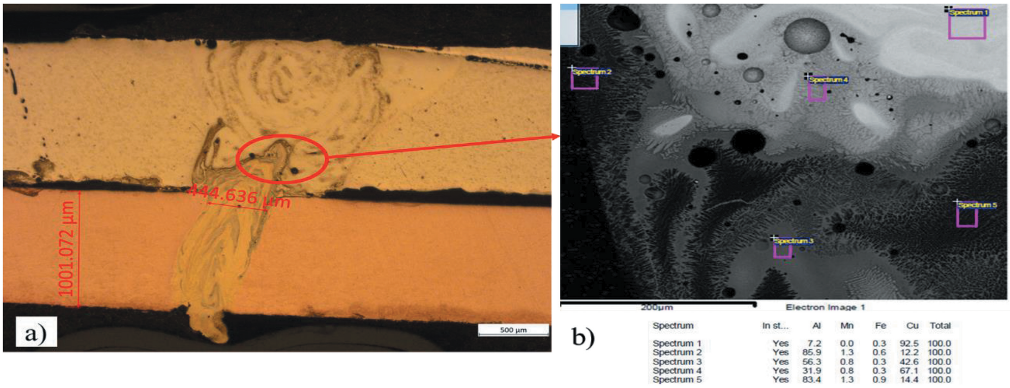
During the study, two different welding modes (conduction and keyhole) were investigated. Dissimilar circular welding pipes were made of Al3003 alloy and pure copper. Welding parameters for both are presented in Table 1.

Keyhole mode in laser welding refers to a process where the laser creates a small, deep vapor cavity (keyhole) in the material being welded. This happens when the laser power density is high enough to vaporize the material, forming a narrow, deep hole surrounded by molten metal. The keyhole is maintained by the pressure of vaporized material and is stabilized by surface tension and the flow of molten material. Optical and SEM images of weld are shown in Figure 2.

Image analysis shows significant mixing of metals and their mutual penetration into each other. This led to the formation of different Al-Cu phases as AlCu, Al_2Cu, Al_4Cu_9 and to

Table 1. Welding parameters.

Mode	Keyhole	Conduction
Power, W	9000	5000
Speed, Rpm	30	15
Focus, mm	0	-30
Beam shape	Point	2-points
Frequency, KHz	200	200
Shielded Gas	Argon	Argon



Spectrum	In st...	Al	Mn	Fe	Cu	Total
Spectrum 1	Yes	7.2	0.0	0.3	92.5	100.0
Spectrum 2	Yes	85.9	1.3	0.6	12.2	100.0
Spectrum 3	Yes	56.3	0.8	0.3	42.6	100.0
Spectrum 4	Yes	31.9	0.8	0.3	67.1	100.0
Spectrum 5	Yes	83.4	1.3	0.9	14.4	100.0

Figure 2. Microscopical investigation of welded joint (keyhole mode): a – optical microscope image, b – electron microscope image and phase analysis.

a significant amount of intermetallic composites. Also, considerable mixing of metals led to defects in the weld - pores and cracks. Using this mode and various welding parameters, none of the experiments shown satisfactory results.

Conduction mode in laser welding occurs when the laser power density is relatively low, and the energy from the laser beam is absorbed by the surface of the material rather than penetrating deeply. In this mode, the heat is conducted through the material primarily by thermal diffusion, causing surface melting without creating a deep keyhole, as in keyhole mode.

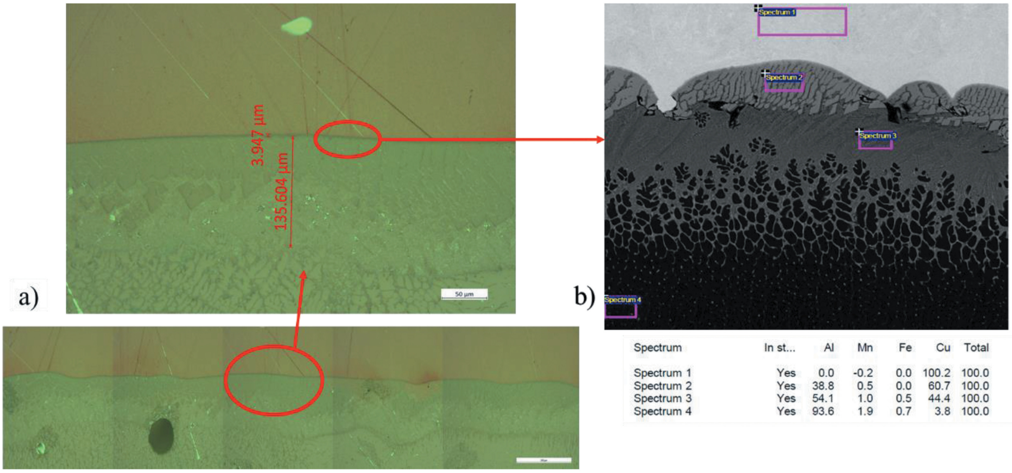
During the experiment, a dynamic beam in the form of two dots was used to distribute the spot energy on the metal surface evenly. The dot with more concentrated energy was directed at copper since it has a higher melting point. The use of dynamic beam shape and conductive mode resulted in much better results than with keyhole mode. Image analysis shows low mixing, narrow intermetallic zone (less than 150 µm), and absence of welding defects (Figure 3).

Tensile testing was performed at a 5 mm/min constant loading rate using an Instron 3369 universal testing machine (equipped with 50 kN Instron loadcell).

As depicted in Table 2, the average tensile strength of the welds achieved through conventional welding and employing a dynamic beam shape in the form of two points was 105-110 MPa. These values corresponded to approximately 75 % of the base metal strength (Al3003 - 147 MPa). Welding was carried out without any filler or welding wire. The leak test showed that all welded joints passed the test at a pressure of 43 atmospheres.

5 CONCLUSIONS

In this paper were investigated conduction and keyhole modes of tube laser welding of dissimilar metals - aluminum alloy 3003 and pure copper. The conduction mode weld was performed at a power of 9 kilowatts and the keyhole mode was performed at a power of 5 kilowatts. It is shown that the mixing of metals in the conduction mode is significantly less than in the keyhole mode. In the conduction mode, the area and size of intermetallic composites are smaller, as well



Spectrum	In st...	Al	Mn	Fe	Cu	Total
Spectrum 1	Yes	0.0	-0.2	0.0	100.2	100.0
Spectrum 2	Yes	38.8	0.5	0.0	60.7	100.0
Spectrum 3	Yes	54.1	1.0	0.5	44.4	100.0
Spectrum 4	Yes	93.6	1.9	0.7	3.8	100.0

Figure 3. Microscopical investigation of the welded joint (conduction mode): a – optical microscope image, b – electron microscope image, and phase analysis.

Table 2. Tensile results.

Sample	Tensile stress at maximum load, Mpa
1	106
2	107
3	110
Al-Base	147
Cu-Base	246

as the number of cracks and pores. To ensure uniform melting of aluminum and copper during the welding, a dynamic beam shape in the form of two points with different energy concentrations was used. A more concentrated point was directed at copper, which is associated with higher reflectivity and a higher melting point. The welded joints showed an average tensile strength of 110 MPa, which is 80% of the base metal, and successfully passed a leak test at 43 atmospheres.

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