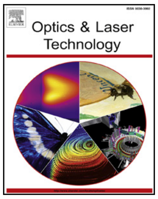
Optics and Laser Technology 111 (2019) 140–145

Contents lists available at ScienceDirect

Optics and Laser Technology

journal homepage: www.elsevier.com/locate/optlastec



Full length article

Microstructures and mechanical properties of laser-arc hybrid welded dissimilar pure copper to stainless steel

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HIGHLIGHTS

- Laser-arc hybrid welding is applied to the welding of copper/stainless steel.
- Effects of laser offset (ΔD) on the weld formations and properties are studied.
- The optimal ΔD to obtain defect-free weld with favorable property is 0.5–1.0 mm.
- The maximum tensile strength of the weld is approximately to copper base metal.

ARTICLE INFO

Keywords:
Laser-arc hybrid welding
Copper/stainless steel dissimilar joint
Microstructure
Mechanical property
Formation mechanism

ABSTRACT

Laser-cold metal transfer hybrid welding was applied to the butt-welding of T2 copper/304 stainless steel (Cu/304SS) dissimilar joint by deviating the laser beam from the edge of the weld seam to the Cu plate. Under the optimal laser offset (ΔD = 0.5–1.0 mm), an acceptable weld with uniform surface morphology and free of visible defect was obtained. All the joints obtained at the optimal ΔD fractured at the Cu side, with the maximum tensile strength reached up to 215 MPa, approximately to that of T2 copper (200–240 MPa). The variations of the weld mechanical properties were well corresponding to the observed microstructure changes. Too small ΔD (< 0.5 mm) resulted in the excess melting of 304SS and formation of the macrosegregations of the Fe-rich peninsula and islands in the fusion zone, which deteriorated the weld mechanical properties. While increasing the ΔD decreased the amount of the melted 304SS, and benefited to from the Cu-rich matrix and inner uniformly distributed Fe-rich particles, which strengthened the weld. However, excess ΔD (> 1.0 mm) weakened the weld because only coarse Cu columnar grains formed.

1. Introduction

The joining of the copper (Cu) and stainless steel combines both the advantages of Cu with excellent electrical and thermal conductivities, and stainless steel with favorable corrosion resistance and mechanical properties. It saves the consumption of Cu, and benefits for the weight reduction and economy saving. The Cu/stainless steel dissimilar joint have been widely used in many industries, such as the aerospace, power generation, nuclear energy, and heat exchanger. However, many differences between the Cu and stainless steel, such as the heat conductivity, melting point, and thermal expansion coefficient, easily cause the defects of thermal stress and solidification cracks in the weld, which greatly weakens the weld mechanical properties [1–3].

Laser welding has been paid widespread attention in the joining of the Cu and stainless steel because of its lower heat input, higher energy density, and more precise control of the heating position relatively to conventional arc welding, which is benefit to avoid the weld defects by effectively controlling the fusion ratio of the Cu and stainless steel [4–7]. Mai et al. [8] obtained a defect-free Cu/steel joint by deviating the laser beam on the steel plate with 0.2 mm, but the insufficient melted Cu due to its high heat conductivity caused the partial metallurgical bonding of the Cu and steel, and thus the poor weld mechanical properties. Yao et al. [9] and Chen et al. [10] both obtained the complete metallurgical bonded Cu/steel dissimilar joints by deviating the laser beam to the steel side, but it was difficult to precisely control the melting amount of Cu, and to suppress the defects of solidification crack and porosity. Shen et al. [11] applied the Nd:YAG pulse laser to the welding of the Cu and stainless steel by deviating the laser beam to the Cu side. They obtained a defect-free weld with excellent mechanical properties by precisely controlling the melting amount of stainless steel, whereas both the high laser power and low welding speed were strictly required because of the great reflectivity of Cu to the

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https://doi.org/10.1016/j.optlastec.2018.09.050
Received 2 April 2018; Received in revised form 16 August 2018; Accepted 23 September 2018
0030-3992/

laser beam.

Laser-arc hybrid welding shows great potential for the welding of metals with high reflectivity such as copper and aluminum, because it can suppress the reflection of the workpiece to the laser beam via the arc preheating, and then increase the absorbed laser energy by the workpiece. Besides, it can increase the welding efficiency, stabilize the welding process, and improve the joint quality by the laser-arc synergic effects [12–17]. For example, Zhang et al. [13] achieved a 4 mm-thick copper weld without preheating via one-pass hybrid welding. More importantly, the laser-arc hybrid welding has been successfully used to join many dissimilar metals [14–18]. Gao et al. [18] joined the titanium and stainless steel via filling the Cu wire, and found the hybrid process effectively reduced the high reflectivity of Cu to the laser beam, and controlled the fusion ratio of the titanium and stainless steel, which was advantageous to obtain the high-quality weld joint. Meanwhile, a new arc welding process of cold metal transfer (CMT) that can precisely control the heat input, arc length, and droplet transfer by the anti-direction pulling motion of the wire via a closed-loop control system has been developed recently [19–21]. The emergence of the CMT technology makes the precise control of the heat input of both the laser and arc energy in the hybrid welding possible. The lower heat input and more stable process can be obtained by the laser-CMT hybrid welding, which improves the welding efficiency and applicability, and shows great potential for the welding of the dissimilar metals.

Our previous studies had proved that accepted Al/Ti, Al/steel and Ti/steel dissimilar joints could be obtained by the laser-CMT hybrid welding [16–18]. However, no reports have been focused on the joining of the copper/stainless steel by the laser-CMT hybrid welding. In this paper, the effects of the laser offset (ΔD) on the microstructures and mechanical properties of the hybrid welded T2 copper/304 stainless steel (Cu/304SS) butt-joint were studied. The relevant results would be of great significance to deepen the understanding of the welding of the copper and stainless steel, and beneficial to the parameters optimization.

2. Experimental

The base metals (BM) used in the experiment were the T2 copper and 304SS with a thickness of both 2 mm. The filler wire was the HS201 with a diameter of 1.2 mm. The chemical compositions of the BM and filler wire are presented in Table 1. Before the welding, the sheets were machined as 100 × 50 mm rectangle, and then milled to remove the oxidized films. The milled surface was cleared and degreased with acetone. The shielding gas from the arc welder was the argon at the flow rate of 20 L/min.

An IPG YLR-6000 fiber laser with a maximum output power of 6 kW, Fronius TPS4000-CMT welder with a maximum electric current of 400 A, and Fanuc 6-axis robot were employed. The laser beam with a wavelength of 1070 nm and a beam parameter product of 6.9 mm mrad was transmitted by a 200 μm core-diameter fiber, collimated by a 150 mm lens, and then focused by a 250 mm lens to get a spot size of 0.33 mm. The arc welder was used in CMT mode. The schematic of the experimental set-up is presented in Fig. 1. During the welding, the laser is the leading heat source. The constant parameters are the inclination angle of laser to vertical direction of 5°, defocus distance (ΔF) of 0 mm, inclination angle of arc torch (α) of 55°, wire extension (CTWD) of 12 mm, and laser-arc distance (D_{LA}) of 3 mm. In the experiment, the laser beam was irradiated on the Cu side with different offsets (ΔD). As shown in Fig. 1, the ΔD is defined as the deviation from the edge of the weld seam to the center of the laser beam on the Cu plate. The welding parameters used are listed in Table 2. When the ΔD is larger than 1.0 mm, the melting amount of 304SS is too little to form an effective Cu/304SS dissimilar weld joint. Thus, only the ΔD in the range of 0–1.0 mm was discussed in the current study.

Table 1
Chemical compositions of the base metal and filler wire.

Material	Chemical composition (wt.%)						
304SS	C	Si	Mn	Cr	Ni	P	S
	0.08	1.00	2.00	18.0–20.0	8.0–11.0	0.045	0.045
T2 copper	Cu	Bi	Sb	As	Fe	Pb	S
	99.90	0.001	0.002	0.002	0.005	0.005	0.005
HS201	Cu	Sn	Si	Mn	P	Pb	Al
	≥98.0	≤0.5	≤0.5	≤0.5	≤0.15	≤0.02	≤0.01

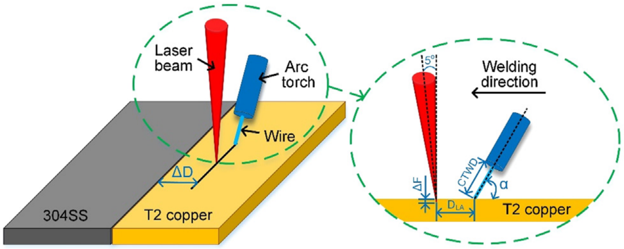

Fig. 1. Schematic of the experimental set-up.

Table 2
Welding parameters.

Joints	Laser power, P (kW)	Arc current, I (A)	Welding speed, v (m/min)	Laser offset, ΔD (mm)
#1	3	60	1	0
#2				0.5
#3				1.0
#4				1.5

After the welding, the metallurgical samples were prepared according to the standard procedures, and etched by a solution of 96 ml ethanol, 2 ml HCl, and 5 g $FeCl_3$. An optical microscopy and a scanning electron microscopy (SEM) were used to observe the microstructures. The chemical composition was tested by an energy dispersive X-ray spectroscopy (EDS). The tensile test was performed according to the standard of ASTM: E8/E8M-11, as shown in Fig. 2. The tensile test was carried out at room temperature with a load speed of 2 mm/min, and the results were the average of three tensile samples. The Vickers microhardness was performed across the weld cross-section below the upper surface of 1.0 mm with a load of 0.98 N for 20 s.

3. Results and discussion

3.1. Weld appearances

Fig. 3 shows that acceptable weld appearances without any defects are obtained when the ΔD is in the range of 0.5–1.0 mm. While the weld with obvious concave and nonuniform upper surface is obtained when the ΔD is 0 mm, as shown in Fig. 3a. The cross-sectional morphologies of the Cu/304SS dissimilar joints indicate that the melting amount of 304SS decreases when the ΔD increases from 0 to 1.0 mm.

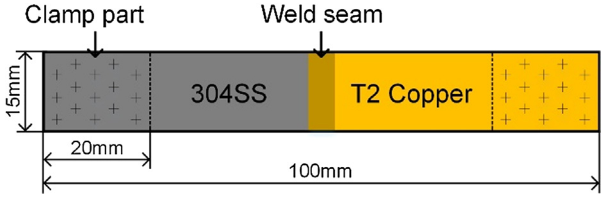

Fig. 2. Schematic of the standard tensile sample.