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Effects of alloying element on weld characterization of laser-arc hybrid welding of pure copper

Kangda Hao, Mengcheng Gong, Yong Xie, Ming Gao *, Xiaoyan Zeng

Wuhan National Laboratory for Optoelectronics (WNLO), Huazhong University of Science and Technology, Wuhan 430074, PR China

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ABSTRACT

Effects of alloying elements of Si and Sn on weld characterizations of laser-arc hybrid welded pure copper (Cu) with thickness of 2 mm was studied in detail by using different wires. The weld microstructure was analyzed, and the mechanical properties (micro-hardness and tensile property), conductivity and corrosion resistance were tested. The results showed that the alloying elements benefit the growth of column grains within weld fusion zone (FZ), increase the ultimate tensile strength (UTS) of the FZ and weld corrosion resistance, and decrease weld conductivity. The mechanisms were discussed according to the results.

1. Introduction

As one of the most important non-renewable and non-ferrous metals, copper (Cu) and its alloys have been widely used in modern industries, such as current-carrying component of batteries, heat exchangers and packing material [1,2]. However, its physical properties are obviously different with those of commonly used steel. For example, Cu has a relatively high thermal conductivity, which is several times higher than that of iron [3]. It increases the energy needed for melting during welding. In arc welding, preheating and slow welding speed were generally necessary for the welding of copper and its alloys to avoid rapid heat dissipation, which forms low performance joints with coarse grains and wide heat-affected zones (HAZ) [1,4,5].

In order to overcome poor weldability caused by the relatively high thermal conductivity, laser welding was employed due to its high energy density, which leads to fast welding speed and high penetration depth without preheating. However, the beam absorptivity of pure Cu to the laser is normally smaller than 5% at room temperature [6], a stable welding process is hard to obtain even by high enough laser power [7–10]. On this basis, dual-beam laser welding [11], power modulated [12] and pre-coated [13] laser welding techniques have been developed to increase the beam absorptivity. The weldability of pure Cu is improved to a certain extent, but problems of low process stability and low mechanical properties of the welds exist yet.

Laser-arc hybrid welding that was put forward by Steen has been considered as one of the most promising fusion welding technique for metallic materials, high efficiency and high stability were obtained by integrating the advantages of both laser welding and arc welding [14,15]. In laser-metal inert gas (MIG) welding of metals, especially in aluminium and magnesium alloys with low beam absorptivity [16–19], high quality welds with good weld formation and mechanical properties were achieved. In laser-arc hybrid welding of pure Cu using HS201 pure Cu wire, the ultimate tensile strength (UTS) and elongation of the weld were about 87% and 56% of base material (BM), respectively [20]. Similarly, in laser-cold metal transfer (CMT) arc hybrid welding of pure Cu using HS211 ($CuSi_3$) wire, the UTS and the elongation of the weld were 84% and 80% of BM, respectively [21].

Previous studies demonstrated that laser-arc hybrid welding has the potential to increase the weldability of pure Cu, but a further study is still needed to further improve its weld properties to match with the BM. Considering that filling wire plays an important role in improving weld properties, but few reports have been addressed on this topic, is this paper, different wires were used to study the effects of alloying elements on the properties of laser-arc hybrid welded pure Cu. The results would be of interest to deepen the understanding and wire composition design in laser-arc hybrid welding of pure Cu.

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* Corresponding author.
E-mail address: mgao@mail.hust.edu.cn (M. Gao).

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2. Experimental procedures

The base metal (BM) used was T2 pure copper with thickness of 2 mm, and the filling wires were HS201 (pure Cu), HS211 ($CuSi_3$), and HS212 ($CuSn_6$) with diameter of 1 mm. The chemical compositions of the BM and the filling wires are listed in Table 1. The sheet size was 100 mm in length and 50 mm in width. Before welding, the specimens were milled to remove surface oxide film, cleaned by acetone and assembled in butt configuration.

As shown in Fig. 1, the welding system was composed of a Fanuc M-710 six-axis robot, an IPG YLS-6000 fiber laser and a Fronius TPS4000 CMT arc welder. The laser beam with wavelength of 1070 nm was transmitted to a collimator with focal length of 150 mm by a 200 μm-diameter transfer fiber, and focused by a lens with focal length of 250 mm to irradiate on the BM with a focal diameter of 0.4 mm. The defocused distance of the laser beam was 0 mm. The angle between laser beam to work-piece surface was 80°, while that between arc torch and work-piece surface was 55°. The arc welder was used in pulsed MIG mode. The wire extension was 11 mm, and the distance between laser beam and wire tip (DLA) was 3 mm.

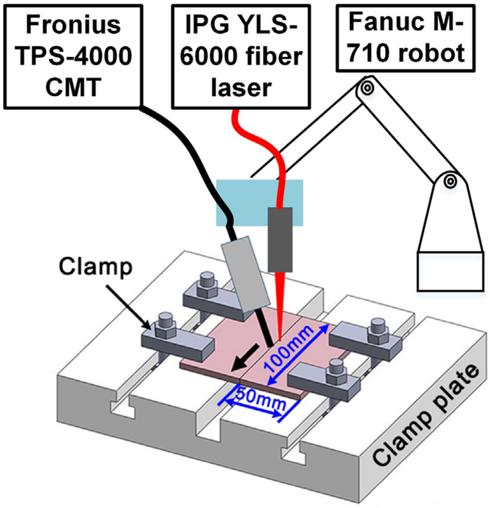

Fig. 1. Arrangement of experimental set-up.

During welding, the shielding gas used was 99.99% argon with the flow rate of 25 l/min. The welding parameters were optimized, which were laser power of 3 kW, welding speed of 1 m/min and arc current of 60 A with wire feeding rate of 4 m/min. For simplification, the welds using wires of HS201 (pure Cu), HS211 ($CuSi_3$), and HS212 ($CuSn_6$) were named as weld-Cu, weld-Si and weld-Sn, respectively.

After welding, the metallurgical and tensile specimens were prepared, as shown in Fig. 2. In order to clearly display the weld microstructure, the metallurgical specimens were chemically etched for 5–10 s by the reagent containing $FeCl_3$ (5 g), HCl (5 ml) and ethanol (100 ml). The microstructure was observed by inverted metallurgic microscope, and the chemical compositions were examined by FEI Sirion-200 field emission scanning electron microscope (SEM) with the function of energy dispersive spectrometer (EDS) test.

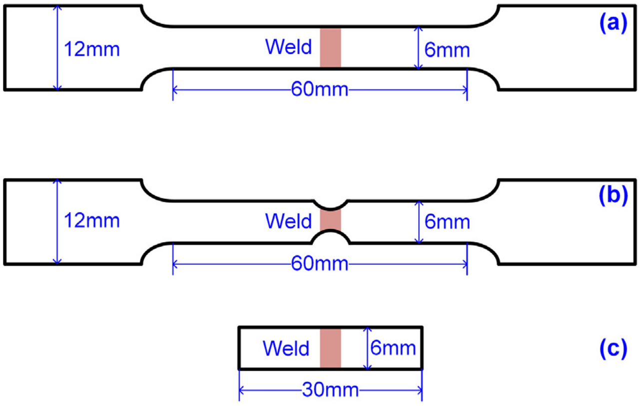

Fig. 2. Dimension of specimens, (a) standard tensile specimen, (b) notch tensile specimen, (c) metallurgical specimen.

The Vickers micro hardness was performed across the weld cross section below the upper surface of 1.0 mm with the load of 1.96 N for 15 s. The tensile test was performed on Shimadzu AGS-X universal mechanical testing machine according to ISO 6892-1:2009, whose dimension size is shown in Fig. 2a. Since some standard tensile specimens fractures in the heat-affected zone (HAZ), which is useless for the analysis of alloying element on the properties of fusion zone (FZ), a non-standard tensile specimen, whose dimension size is shown in Fig. 2b, was designed to ensure all the welds fracturing in the FZ. The tensile results were the average of two specimens.

The weld resistance was tested on CHT3540-1 DC resistance tester with the dimension as shown in Fig. 3. The result was the average of ten tests. Both the top and the root reinforcements of the weld were milled to eliminate their impacts. After the test, the weld conductivity (γ) was calculated by Eq. (1).

$$\gamma = \frac{L}{RS} \tag{1}$$

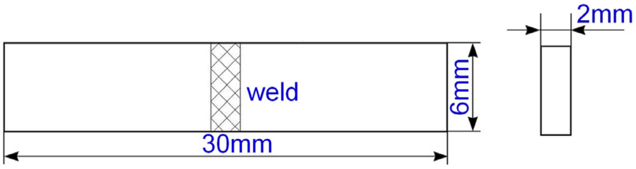

Fig. 3. Dimension size of conductivity specimen.

where R is the measured resistance, S is the cross area of the tested specimen, and L is the specimen length.

The weld corrosion resistance was tested by Corrtest CS310 electrochemical workstation using solution of 3.5 wt% NaCl. The

Table 1
Chemical compositions of BM and filling wires (wt.%).

Materials	Fe	Pb	Sb	Si	Mn	Sn	Al	P	Cu
BM	≤0.005	≤0.005	≤0.002	/	/	/	/	/	Bal.
H201	/	/	/	0.30	0.30	1.0	/	/	Bal.
H211	0.3	≤0.02	/	2.8–4.0	0.5–1.5	0.2	0.01	0.02	Bal.
H212	0.05	0.02	/	0.5	0.1–0.5	5.5	0.01	0.02	Bal.