Journal of Manufacturing Processes 27 (2017) 207–213

Contents lists available at ScienceDirect

Journal of Manufacturing Processes

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

Technical Paper

Stabilization mechanism and weld morphological features of fiber laser-arc hybrid welding of pure copper

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ARTICLE INFO

Article history:
Received 20 February 2017
Received in revised form 19 April 2017
Accepted 9 May 2017

Keywords:
Hybrid welding
Copper
Stability
Laser keyhole
Arc

ABSTRACT

Process characterization of laser-arc hybrid welding of pure copper was studied. The morphological features and the porosity of the welds were measured by optical microscope and X-ray non-destructive test, respectively. Process stability was characterized by the numbers in interruption and short circuit of the arc, which were counted from the waveform of arc current. The dynamic behaviors of molten pool, keyhole and droplet transfer were observed by high speed video camera. The results showed that the process was unstable in single laser welding and single arc welding, but could be easily stabilized by hybrid welding. Accepted weld and stable process could be obtained under the optimized parameters, which were the laser power around 4 kW, the arc current higher than 120 A and the welding speed lower than 1.5 m/min. The process stabilization was attributed to two reasons. Firstly, laser keyhole was stabilized by homogenizing and decreasing of dynamic vapor pressure on keyhole rear wall. Secondly, the arc wandering was avoided by keyhole fixation. Both of the reasons prevented the fast heat loss caused by the high heat conductivity of pure copper.

1. Introduction

Copper (Cu) and its alloys have been widely used in power, chemical, shipbuilding and heat exchange industries due to the excellent properties such as high electrical conductivity and good corrosion resistance. Unfortunately, Cu has been hard to be welded efficiently because of high thermal conductivity. During arc welding, the coarsening of grain size easily occurs, and the penetration depth is very shallow because of the low power density [1,2]. Usually, preheating is necessary to get an accepted arc weld [3]. Laser welding has the potential to improve the efficiency of Cu welding because of the high power density, but the laser absorptivity of Cu is lower than 5% at room temperature. It causes an unstable process [4,5], with bad weld morphologies and plenty of spatters [6–9]. Many studies have been carried out to improve the stability. Hess studied double laser beam welding of pure Cu, and found that the spatters reduced by 80% compared to single laser welding [10]. Heider found that the spatters in laser welding of Cu alloys could be reduced by power modulation, but the porosity at weld root was still high [11]. Hao improved welding efficiency by using graphite coating to increase the laser absorptivity, but the formation of graphite slag decreased the mechanical properties [12]. Although some achievements were obtained in previous studies, the problems such as bad weld morphologies and high porosity existed yet.

Because of the advantages of high efficiency, strong gap ability, deep penetration depth and good mechanical properties by combining laser beam with arc column [13], laser-arc hybrid welding has been demonstrated a good technique to improve the weldability of Ti, Al and Mg alloys. Li found that the welding speed of laser-arc hybrid welding of pure Ti was about seven times faster than that of metal inert gas (MIG) welding only [14]. Yan obtained good 1420 Al-Li alloy weld by CO_2 laser-MIG welding [15]. Our previous studies showed that the ultimate tensile strength and the elongation of laser-arc welded AZ31 Mg alloy were 97.8% and 87.5% of base metal, respectively, far higher than those of laser weld [16]. These studies suggested that laser-arc hybrid welding would be potential to obtain high quality welding of pure Cu.

Presently, our studies and Zhang et al. [17,18] demonstrated that accepted pure Cu weld could be obtained by laser-metal inert gas (MIG) hybrid welding. During welding, it is of interest to found that unstable keyhole collapse and arc interruption frequently occurred, but no studies have been addressed on these phenomena. This paper then emphasized on this topic, and discussed the mechanisms by laser-arc interaction.

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http://dx.doi.org/10.1016/j.jmapro.2017.05.009

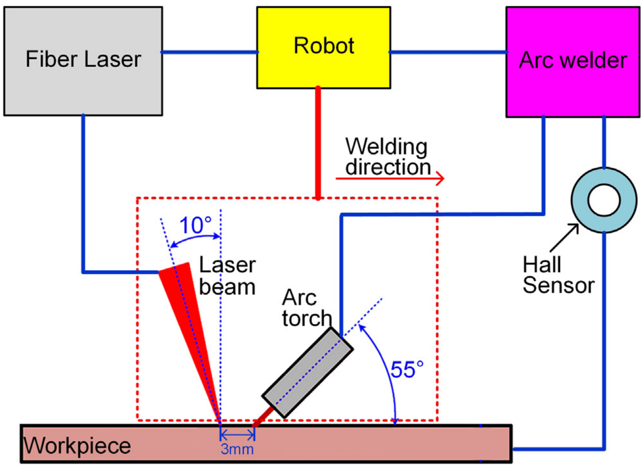

Fig. 1. Schematic diagram of experimental set-up.

2. Experimental procedures

The welding system consisted of an IPG YLR-6000 fiber laser, a FRONIUS TPS4000 MIG arc welder and a FUNAC M-710ic/50 robot, as shown in Fig. 1. The fiber laser was featured by a continual beam with the wavelength of 1070 nm and the beam parameter product (BPP) of 6.9 mm mrad. The laser beam was transmitted by a 200 μm core-diameter fiber, collimated by a lens with 150 mm focal length, and focused by a lens with 250 mm focal length to get a spot size of 0.33 mm. The wire stand-off was 11 mm. The angle of laser beam to vertical direction was 10°, while the angle of arc torch to workpiece surface was 55°. The distance between laser beam and wire tip (D_{LA}) was 3 mm. The arc current was measured and recorded by a hall sensor. The dynamic behaviors of molten pool, laser keyhole and arc droplet transfer were recorded by a PHANTOM V710 high-speed camera with a Cavitar Cavilux HF illumination, whose frame rate and exposure time are 6000 fps and 1 μs, respectively.

The base material (BM) was T2 pure Cu. The 5 mm-thick samples were employed to study weld morphology and process stability, while the 4 mm-thick samples were employed to study weld porosity because full penetration weld could be obtained at this thickness. All samples were machined as the dimension of 100 mm × 30 mm before welding. The filling wire was 1.2 mm-diameter pure Cu wire (HS201). The chemical compositions of the BM and the wire are listed in Table 1 and Table 2, respectively. The shielding gas of arc torch was 99.99% Ar with a flow rate of 25 l/min. The welding was carried out on bead-on-plate configuration. For simplification, laser power was named as P, arc current was named as I, and welding speed was named as v.

Table 1
Chemical compositions of T2 copper (wt%).

Material	Cu	Bi	Sb	As	Fe	Pb	S
T2-copper	≥99.90	≤0.001	≤0.002	≤0.002	≤0.005	≤0.005	≤0.005

Table 2
Chemical compositions of filling wire (wt%).

Wire type	Cu	Pb	Sn	Al	Mn	P	Si
HS201	≥98.00	0.02	1.0	0.01	0.30	0.15	0.30

After welding, the metallurgical samples were prepared according to standard procedures, and etched by a solution of 5 g $FeCl_3$, 5 ml HCl and 100 ml H_2O with the etching time of 10 s. The weld morphology was observed and measured by optical microscope. The weld porosity was detected by X-ray non-destructive test (X-ray NDT), and was defined as the fraction of pore area to the whole area of the weld in X-ray NDT photos.

During hybrid welding, it was demonstrated that laser-arc interaction benefits the arc ignition and increases the degree of arc ionization, and then causes the variation of arc voltage and current. Therefore, the waveform of arc current was used to characterize the effect of welding parameters on laser-arc interaction and process stability. In order to avoid the disturbance at initial and terminal stages, only the waveform in the middle three seconds of each welding was selected for data statistics. As shown in Fig. 2, it was found that the instability could be classified by two types, arc interruption (AI) and short circuit (SC). The AI occurred at the arc striking stage when the droplet did not form at wire tip, corresponding to a shallow sunken discontinuity on weld surface because there was no droplet transition. The SC occurred at the droplet transition stage when the liquid bridge between droplet and molten pool busted off, and was corresponding to the spatters and poor weld morphology because there was a strong impact on molten pool. This good agreement demonstrated that the numbers of AI and SC form arc current waveform are suitable to characterize the effects of welding parameters on process stability. The larger the numbers of AI and SC, the worst the process stability.

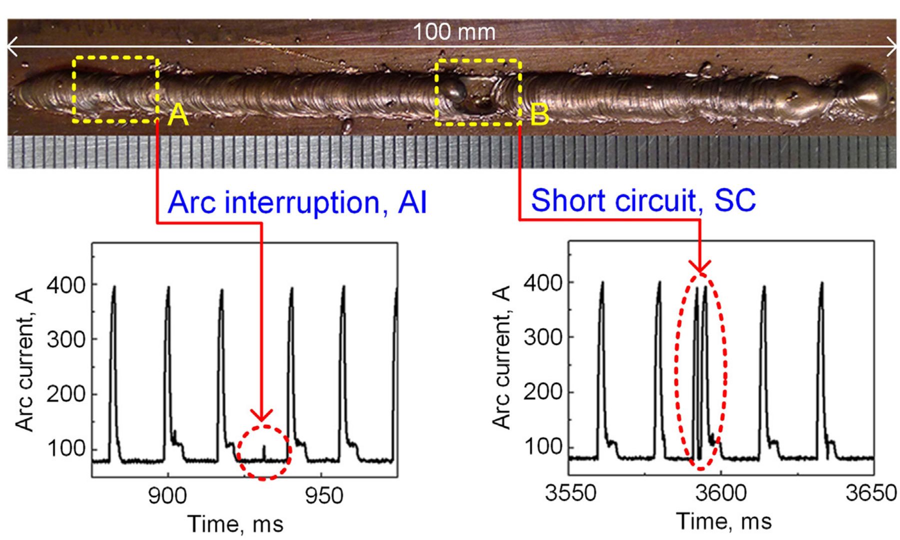

Fig. 2. Correspondence between weld surface morphologies and arc current waveform, where the welding parameters is P = 4.0 kW, I = 80 A and v = 1 m/min.