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Fiber laser welding of austenitic steel and commercially pure copper butt joint

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ABSTRACT

The fiber laser welding of austenitic stainless steel and commercially pure copper in butt joint configuration without filler or intermediate material is presented. In order to melt stainless steel directly and melt copper via heat conduction a defocused laser beam was used with an offset to stainless steel. During mechanical tests the weld seam was more durable than heat affected zone of copper so samples without defects could be obtained. Three process variants of offset of the laser beam were applied. The following tests were conducted: tensile test of weldment, intermediate layer microhardness, optical metallography, study of the chemical composition of the intermediate layer, fractography. Measurements of electrical resistivity coefficients of stainless steel, copper and copper–stainless steel weldment were made, which can be interpreted or recalculated as the thermal conductivity coefficient. It shows that electrical resistivity coefficient of cooper–stainless steel weldment higher than that of stainless steel. The width of intermediate layer between stainless steel and commercially pure copper was 41–53 µm, microhardness was 128–170 $HV_{0.01}$.

1. Introduction

Currently, fiber laser welding becomes a very popular manufacturing process. Fiber lasers have a wavelength ten times less than that of widely spread CO_2-lasers, resulting in a higher absorption degree of laser energy by the treated metal. In the case of CO_2-lasers, actively used for welding in the last 30 years, a large number of experimental studies were conducted, including those for welding of dissimilar materials [1–3]. Welded joints of dissimilar materials are widely used in the automotive, oil, aerospace and nuclear power industries. Components and details produced by welding of dissimilar materials combine high strength, sufficient ductility, corrosion resistance, good electrical and thermal conductivity. The stainless steel and commercially pure copper have significant differences such as chemical composition and thermomechanical properties it makes the dissimilar welding of these materials difficult. The thermal conductivity and thermal expansion coefficient of copper are significantly higher than those of the stainless steel. Widely spread welding techniques to obtain the welded joints of dissimilar metals are arc welding [2,4,5], diffusion [6–9], friction welding [10], friction stir welding [11], ultrasonic welding [12–15], welding-brazing [13–17], explosive welding [18], rolling welding [19], laser welding [20–30], hybrid laser-arc welding [31–35], and others.

All of these methods have advantages and disadvantages, such as low productivity, high energy consumption, formation of intermetallic layer within the thermal welding methods, narrow applicability of particular method and others [7,36]. The intermetallic layer becomes larger when metal during welding of dissimilar materials stays in the molten state for a long time forming intermetallic compounds [22].

Welding of austenitic steel and commercially pure copper is an important task for the cooling systems and heat exchangers, in order to enhance the heat transfer through the copper, which in turn will reduce the weight of construction [4,6,17,18,20,36]. In contrast to aluminum–copper welding process, welding of austenitic steel and commercially pure copper is a simpler problem to be solved, due to the metallurgical compatibility and lack of formation of intermetallic compounds [36]. The diagram of the binary system Fe–Cu [37] shows that the iron can be alloyed with copper in all ratios, with the maximum solubility in δ-Fe 6.5%, in γ-Fe 8%, in α-Fe 1.4% at 850 °C. Copper dissolves 4% of iron at 1094 °C and 0.2% at 650 °C. Based on the Darken-Gurry solubility diagram, mutual solubility was determined by the similarity of the crystal lattices of components, difference in atomic radius and electronegativity value [38]. Metals Cu, Ni, Co, Fe has a slight difference of atomic radiuses and electronegativity, respectively, in fusion welding these materials can be dissolved in each other forming a row of solid solutions. Nowadays a lot of research is conducted on laser welding and brazing of dissimilar materials, but few authors examine the operational properties of the obtained material.

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Casalino et al. [22,39] in their study described the obtaining of the welded joint AA5754 and T40 butt joint, authors investigated the effect of the offset of the laser beam on the side of titanium, within this method, laser beam melts only titanium, and the fusion of aluminum was achieved via heat conduction. Also authors assessed the heat input and its impact on the size of the intermetallic layer, and thus on the mechanical properties. In case of welding of stainless steel and commercially pure copper, offset of the laser beam towards the stainless steel can be an effective technique process, as copper is almost not melted by laser radiation, and stainless steel is melted to the depth of 3–4 mm using the same welding parameters.

In order to produce a solder joint Zhang [17] used tungsten/metal gas suspended arc welding, which allows to minimize the heat input, the arc was directed not on the base metal, but on the solder metal, it helped to reduce heat input and avoid copper-penetrating crack.

Laser welding of dissimilar metals such as copper and steel is an important task for many industries, this applies to the welding of large thicknesses material (3–5 mm) and the welding of small thicknesses material (0.2–0.6 mm), as well as various configurations of the weldments (T-joint, overlap, butt joint).

Laser brazing with the use of a filler material was described by Suga et al. [40], which is even more simple joining method, however, it requires use of a filler material, which complicates the technology and will affect the thermal and electrical conductivity of the weldment.

Chen et al. [41] investigated the influence of process parameters of welding speed and CO_2-laser power as well as the offset and incline angle of the laser beam in the direction of the stainless steel. The weldment can be obtained as fusion welding or welding-brazing of liquid stainless steel to solid copper. Yao et al. [3] proposed a new method to perform the cooper-steel CO_2-laser welding. The scarf joint geometry was used, i.e., the sides of the copper and steel were in obtuse and acute angles, respectively. During the welding process, the laser beam was fixed on the steel side and the dilution ratio of copper to steel was controlled by properly selecting the deviation of the laser beam.

This work is aimed at obtaining of fiber laser butt welded joints of austenitic steel and commercially pure copper without the use of filler or intermediate materials. Three process variants of offset of the laser beam were applied:

- with offset of laser beam onto stainless steel side;
- using lead-in plate and then offset to butt joint;
- with wobbling of laser beam and offset onto stainless steel.

Influence of process variants on the quality of the welds was studied. Welding was performed at a speed of 10 mm/sec, it was used for longer interaction time of the liquid stainless steel with solid copper. Tensile tests, microhardness measurements of intermediate layer, optical metallography, study of the chemical composition of the intermediate layer, fractography were performed. The electrical resistivity coefficients of stainless steel, copper and weldment copper–stainless steel were measured, which can be interpreted or recalculated as the coefficient of thermal conductivity.

2. Experimental procedure

2.1. Materials

Fig. 1 shows the binary phase diagram of Fe-Cu. 321 stainless steel was chosen for experimental research, delivery condition – rolling (210–225 $HV_{0.1}$), dimensions of workpieces before welding (L×W×T) 70×50×3 mm. Commercially pure copper, delivery condition – cold rolling (95–100 $HV_{0.1}$) geometric dimensions are the same. The chemical composition is shown in Table 1. The edges of the workpieces have been cut off using the cutting machine Buehler AbrasiMatic 300, it had a relatively low roughness. The 3 mm thickness of workpieces was chosen to make it easier to carry out the mechanical tests and to make samples for determination of electrical resistivity.

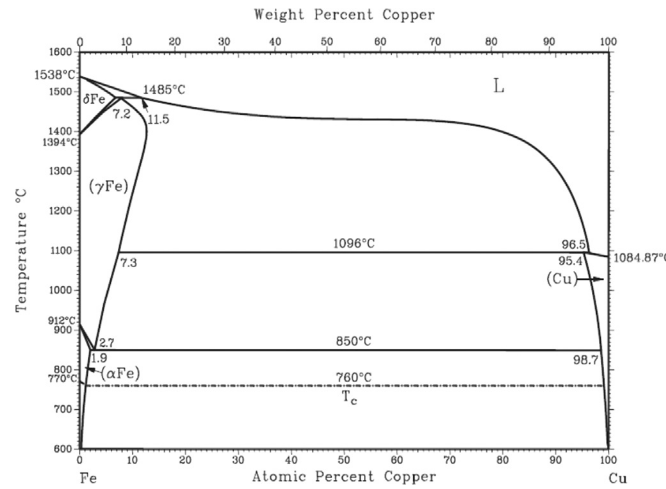

Fig. 1. Phase diagram of Fe-Cu.

2.2. Experimental equipment

Welding was performed on the set of KUKA KR 120R 2700 extra HA, fiber laser LS-30 of “IPG - Photonics” (USA), the welding head LK-690, KUGLER GmbH. The wavelength of the fiber laser was 1070 nm, focal length was 450 mm. Focal distance varied between 0–12 mm, argon with purity 99,99% was used as a shielding gas to protect the top part of molten pool, distance between shielding tubes and surface of workpiece was 1.0–1.2 mm, the flow rate of shielding gas was 18 l/min. Welding of the workpieces was performed using single pass from one side. The laser beam angle of inclination relative to the workpieces was 90°.

Before and after welding the samples were cut on the Buehler AbrasiMatic 300 equipment. Marble (HCl – 100 sm^3, $CuSO_4$ – 20 g, H_2O – 100 sm^3) reagent was used to identify the microstructure. Study of the microstructure was conducted using the microscope Axiovert Observer.D1m of “Carl Zeiss”, metric measurements were carried out using Thixomet image analyzer, microhardness was measured using Remet HX 1000 manual equipment with the load being 100, 25 and 10 g. Mechanical tests were conducted on the tensile testing machine Shimadzu AG-5kNX, fractography and chemical composition analysis were conducted on SEM Carl Zeiss AURIGA CrossBeam (FIB-SEM) Zeiss NVision 40.

2.3. Process variants and welding parameters

The pure copper has a low absorption coefficient of the fiber laser with wavelength 1070 nm. For the obtained welded joint three welding process variants of offset of the laser beam were applied:

- with offset of laser beam onto stainless steel side, shown in Fig. 2.1;
- using lead-in plate and then offset to butt joint shown in Fig. 2.2;
- with wobbling of laser beam and offset onto stainless steel shown in Fig. 2.3.

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Plates of copper alloy and stainless steel were remelted under the same conditions before welding experiments (Fig. 3) to indicate depth and width of penetration. Copper was almost not remelted by laser radiation as opposed to stainless steel, it was decided to use the defocused laser beam (+9, +12 mm), with laser offset onto steel. Microsections were prepared from remelted samples to evaluate the depth of penetration and width of the weld pool. The presented results