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Interface microstructure and mechanical properties of laser welding copper–steel dissimilar joint

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ABSTRACT

Relatively the high reflectivity of copper to CO_2 laser led to the difficulty in joining copper to steel using laser welding. In this paper, a new method was proposed to complete the copper–steel laser butt 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. The offset of laser beam depended on the scarf angle between the copper and steel, the thickness of plate and the processing parameters used in the laser welding. The microstructure near the interface between Cu plate and the intermixing zone was investigated. Experimental results showed that for the welded joint with high dilution ratio of copper, there was a transition zone with numerous filler particles near the interface. However, if the dilution ratio of copper is low, the transition zone bursting only generated near the upper side of the interface. At the lower side of the interface, the turbulent bursting behavior in the welding pool led to the penetration of liquid metal into Cu. The welded joint with lower dilution ratio of copper in the fusion zone exhibited higher tensile strength. On the bases of the microstructural evaluation at the interface of the welded joint, a physical model was proposed to describe the formation mechanism of the dissimilar joint with low dilution ratio of copper.

1. Introduction

In the power-generation industries, the copper–steel combinations have often been widely used due to their high electrical conductivity and stiffness. However, the joining of copper to steel has become a challenging task facing modern manufactures. The butt welding of copper to carbon steel belongs to joining of dissimilar metals. However, the obvious material mismatches, such as the chemical properties and thermomechanical properties, between the copper and carbon steel make the dissimilar welding of these materials difficult. Hence, it is difficult to achieve defect-free copper–steel dissimilar joints using the conventional methods, such as shielded metal arc, gas tungsten arc, gas metal arc, and submerged arc, etc. In the past decades, the electron-beam welding was often used in the fabrication of the dissimilar joints [1,2]. However, the quality of the joints was often influenced by the vacuum conditions used in the welding process. By comparing with electron-beam welding, the laser welding is not restricted by vacuum condition. Hence, using the laser welding to fabricate the dissimilar joints has been attractive in the recent years [3–5]. However, the detailed research on the microstructure and mechanical properties of the laser-welded copper–steel dissimilar joints were relatively few. Mai and Spowage [6] proposed a processing map in which butt joints were fabricated by focusing the laser beam of 0.2 mm into the steel. In such a case, most of the laser energy was absorbed in the steel and the amount of copper dissolved in the molten steel was very limited. However, the complete metallurgical bonding could not be achieved at the interface between copper plate and molten steel. Phanikumar et al. [7] have studied Fe–Cu dissimilar couple, and found the interface near the copper side was in the jagged shape.

Using the commonly welded structure for copper–steel dissimilar joints, in which laser beam is focused on the center of butt welding joint, the following problems may occur. First, the reflectivity of copper to 10.6 μm wavelength CO_2 laser is up to 98.4% [8], leading to the low absorptivity of copper. Second, the thermal expansion coefficient and thermal conductivity of copper are significantly higher than those of the low-carbon steel [8,9]. Hence, during the welding process, the large misfit strain and the residual stresses will be inevitably generated in the joint, leading to solidification cracking of it. Third, the porosity is a common defect originating from hydrogen which is highly soluble in liquid

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copper. Fourth, in laser welding, the high-temperature gradients may result in obvious phase transformation, leading to excessive hardness in the fusion zone. The modified structural design of the copper–steel dissimilar joint was necessary to avoid the occurrence of the above problems.

In this paper, the butt welding of copper and low-carbon steel (i.e., E235A) using a continuous CO_2 laser beam was investigated. A scarf structure was designed for Cu–Fe dissimilar joint. The fusion-control process of copper and the microstructure near the Cu–steel interface, and the mechanical properties of joints were experimentally investigated. The formation mechanism of the joint was described. The topics in this paper could provide some important insights on the development of designing methodology and process optimization for laser welding dissimilar joints.

2. Experimental procedures

2.1. Materials and structural design of joints

The binary phase diagram of Fe–Cu is shown in Fig. 1 [10]. It can be seen that there exists one peritectic reaction point in the iron-rich side. The melting temperature of pure Fe is 1538 °C and the peritectic point is 1485 °C. At the peritectic point, δFe is in equilibrium with γFe containing 7.2 wt% Cu and L containing 11.5 wt% Cu. In the copper-rich side, there exists another peritectic reaction point (i.e., 1096 °C) existing, where the maximal solubility of Fe in Cu is about 3.5%. Generally, if the temperature interval between liquidus and solidus temperature is narrow, dwell time of liquid weld metal becomes relatively short. In such a case, it is possible to minimize the gas porosity since the gas is under restraint over a short time during weld metal solidification. In contrast, if the temperature interval is wide, a large amount of gas will be dissolved into the molten weld metals, leading to high porosity. Moreover, the solidification of the molten pool will be in mushy solidification mode in the subsequent cooling process, leading to the increment of the possibility of cracks and shrinkage porosity in the intermixing zone [11]. Hence, the cooling temperatures of Cu–Fe joints containing Cu lower than 7.2 wt% should be controlled from 1485 to 1538 °C, while those of the joints containing Cu higher than 96.5 wt% should be controlled from 1096 to 1084 °C. But, in the laser welding process, the amount of soluble hydrogen in liquid welding metal containing Cu higher than 96.5 wt% should be higher than the one containing Cu lower than 7.2 wt%. In addition, higher laser power should be used for the melting of joint with higher amount of Cu. Hence, controlling the dilution ratio of Cu to be lower than 7.2 wt% Cu is possible to improve the quality of the laser welded Cu–Fe dissimilar joint.

Considering the high-temperature gradients in the joint through the thickness direction during the laser-welding process, the scarf geometry of the joint was used, as shown in Fig. 2, where α and β denote acute and obtuse angles at the sides of Fe and Cu plates, respectively, d is the offset of laser beam on the steel plate, and t denotes the defocusing amount. The sum of α and β angles is

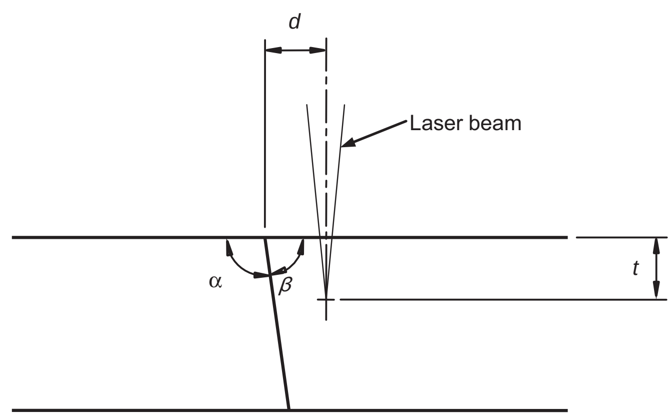

Fig. 2. Scheme of butt welding by laser.

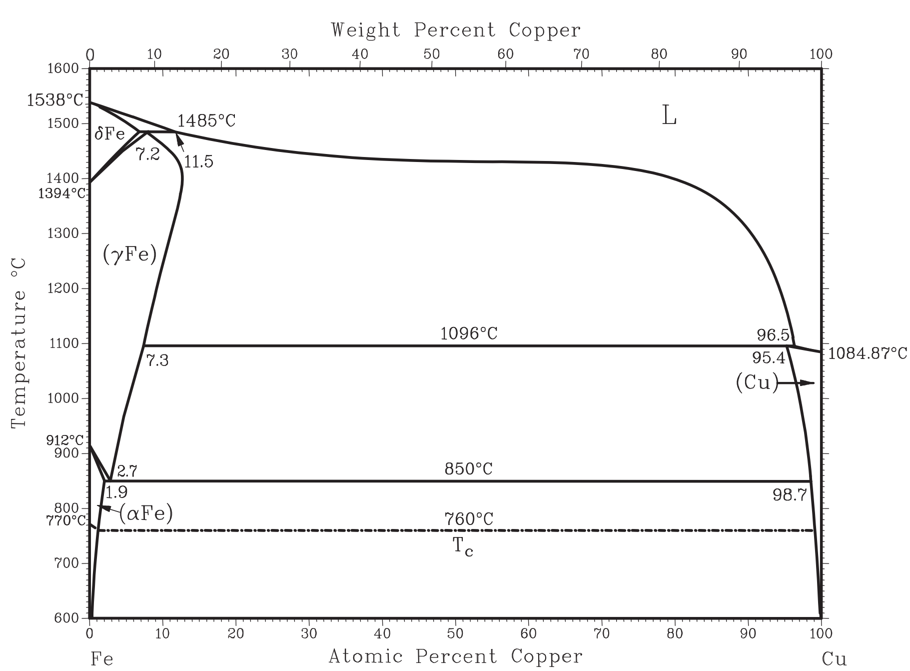

Fig. 1. Phase diagram of Fe–Cu.