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Effect of adding powder on joint properties of laser penetration welding for dual phase steel and aluminum alloy

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ABSTRACT

The experiments of laser penetration welding for dual phase steel and aluminum alloy were carried out, and the effect of adding Mn or Si powder on mechanical properties and microstructure of the weld was investigated. Some defects, such as spatter, inclusion, cracks and softening in heat affected zone (HAZ), can be avoided in welding joints, and the increased penetration depth is obtained by adding Mn or Si powder. The average tensile-shear strength of Si-added joint is 3.84% higher than that of Mn-added joint, and the strength of both joints exceeds that of no-added joint. In the case of adding Mn powder, small amount of liquid Al is mixed into steel molten pool, and the Al content increases in both sides of the weld, which leads to the increased weld width in aluminum molten pool. Thus, transverse area increases in jointing steel to aluminum, which is significant for the improved tensile-shear strength of joints. As far as adding Si powder is concerned, it is not the case, the enhancement of the joint properties benefits from improvement of metallurgical reaction.

1. Introduction

Recently, there has been an increasing demand for light weight and high specific strength materials in the automotive industry due to fuel consumption and protecting environment [1]. Joining steel to aluminum has been recognized as one of the major measures [2–8]. However, it is difficult for welding of steel and aluminum because a number of brittle intermetallic compounds (IMCs) are easily formed during welding. Laser welding can shorten the metallurgical reaction time and restrict the formation of IMCs with high heating and cooling rates. Sierra et al. [5] suggested a steel-on-aluminum overlap configuration, and thought the formation of IMCs is suppressed effectively by controlling steel penetration in aluminum. Later, various researchers have been ste pping up efforts to join steel to aluminum by using this method [9–11]. However, these investigations only optimized the joint properties with respect to process parameters or heat source.

Improving the metallurgical reaction is an effective way of enhancing the joint properties. Usually, adding an interlayer can improve the metallurgical reaction of molten pool for laser welding. In our primary investigation, it was found that adding Pb-foil interlayer can improve the mechanical properties of the laser welding joint in steel-on-aluminum overlap configuration [12]. Chen et al. [13,14] showed that when Ni-foil was added at the welding interface of steel and aluminum, similarly, the joint properties is also improved. Yang et al. [15] investigated laser welding steel to aluminum with Cu-foil, and found that Cu-foil inhibits the Al diffusion to the steel side, but the joint strength is not improved. In this paper, the experiments of laser penetration welding for dual phase steel and aluminum alloy were carried out, and the effect of adding Mn or Si powder on mechanical properties and microstructure of the weld was investigated. The strengthening mechanism of the joint was clarified.

2. Materials and experimental procedure

The materials used in the experiment are 6016 aluminum alloy with composition of Al-1.2Si-0.4 Mg-0.5Fe-0.2Mn (wt.%), and DP590 dual phase steel with composition of Fe-0.15C-0.6Si-2.5Mn (wt.%). The sizes of them are $100 \times 30 \times 1.2$ mm and $100 \times 30 \times 1.4$ mm, respectively. Steel sheet is placed on aluminum in an overlap configuration due to aluminum with high reflectivity. Mn or Si powder, with 99.9% purity, 75-μm average size, and 0.1 mm thick is added between the two plates as interlayer, as shown in Fig. 1.

Welding heat source is provided by YLS-4000-CL fiber laser, main laser technical parameters are shown in Table 1. Prior to welding, the surfaces of sheet samples are cleaned with acetone to remove grease and residues. Sandpaper is used to remove the

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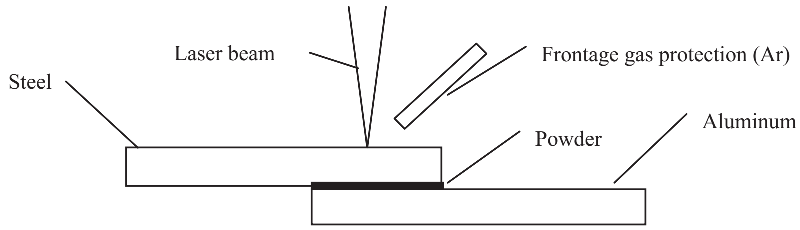

Fig. 1. Schematic illustration of steel/aluminum welding set up.

Table 1
Main technical parameters of fiber laser.

Parameter	Laser powder (kW)	Laser mode	Angle alpha of the beam divergence (rad)	Focal length f (mm)	Focal spot d (mm)	Wavelength λ (nm)
Value	≤4.0 (CW)	TEM_{00}	<0.15	200	0.4	1070

oxide layer of aluminum alloy surface, Mn or Si powder is distributed evenly on the aluminum surface by using acetone. When it is dry, laser lap welding test is made. Laser beams are endicularly incident to upper surface. The protective gas is argon which is used to protect the front and back of weld at the same time. Deep penetration laser welding test with Mn or Si powder is carried out to obtain a good weld not only a weld with sufficient penetration but also an acceptable weld surface. The optimal process parameters are determined as follows: welding power is 2000 W, welding speed is 50 mm/s, the defocus distance is +2 mm, and the rate of flow of the Ar protective gas is 15 L/min. The process parameters of adding powder are the same as that of no powder in order to identify the effect of adding powder on microstructure and properties of the weld.

After welding, test specimens are cut, then, standard metallographic preparation procedures are utilized. Microstructure, fracture morphology and interface elements distribution of the welds are performed by FEI Quanta 200 scanning electron microscopy equipped with spectrometer (EDS) and electron back-scattered diffraction (EBSD) probe. Crystalline phase of joints are identified by X-ray diffraction (XRD). Both tensile and shear forces are applied to the interface during test due to nonsymmetric configuration of the tensile test samples. Hence, in the current study, the joint strength is given in N/mm(failure strength divided by the width of tested specimen) since it is difficult to separate tensile and shear stress. According to the BS EN 1002-1:2001 standard, the tensile-shear tests are operated at room temperature using INSTRON 5569 at a crosshead speed of 1 mm/min. Average joint strength is calculated from three tensile specimens.

3. Results and discussion

3.1. Surface morphology and microstructure of joints

Fig. 2 shows the influence of adding powder on the surface morphology of joints. When Mn or Si powder is added, some defects, such as spatter, inclusion, cracks can be avoided under the condition of the optimized process. In addition, continuous uniform weld surface with rules pattern is easily observed. Further analysis for macro-morphologies of weld cross section is presented in Fig. 3. Same thing happens, cracks and pores are also not obvious. The top of the molten pool is wide, while below is narrow, and the ratio of depth and width is bigger. An typical characteristics of "keyhole" finger can be seen. This exhibits welding mode is laser penetration welding in this study. However, when Mn or Si powder is added, welding penetration depth both increase compared with that of no-added joint, and the depth of Si-added joints exceeds that of Mn-added joints, which is shown in Fig. 3a–c, respectively.

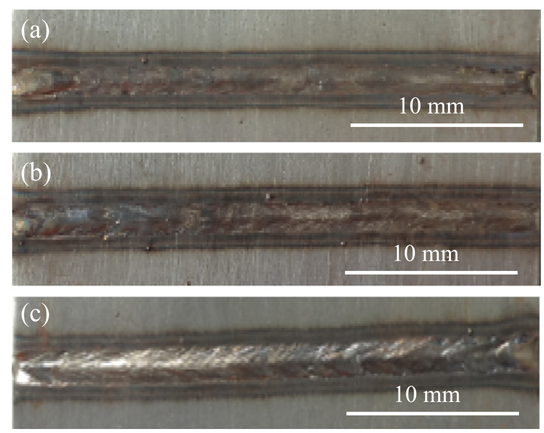

Fig. 2. Surface of the steel/aluminum weld (a) No powder, (b) Mn powder and (c) Si powder.

As is known, heat flux density is both determined by laser energy in laser penetration welding with/without powder, if welding parameters is kept the same, surface temperature of the upper dual phase steel should be not changed, but the lower aluminum alloy is affected by the air or powder layer. In normal conditions, thermal conductivity of the air is about 10^{-4} to 10^{-6} W/(mK), while that of the Fe-based or Al-base is about 10 to 10^{3} W/(mK). Consequently, air layer will hold back heat conduction, and decrease the cooling rate of joints. However, thermal conductivity of Mn or Si powder is higher than that of the air, when it replaces the air layer, the upper dual phase steel and the lower aluminum alloy will be connected tighly. As a result, blocked phenomenon of heat quantity is significantly improved, and heat quantity of the upper duel phase steel is quickly transferred to the lower aluminum alloy, thus the thermal conduction rate mounts up and the cooling rate of joint ascends. Hence, the increased welding penetration depth is obtained with the addition of powder.

In addition, laser energy absorption rate can be calculated by using the following expressions [16]:

$$\alpha = 0.365\sqrt{\frac{\rho}{\lambda}} \tag{1}$$

where α refers to laser energy absorption rate, ρ and λ are the resistivity and laser wavelength. Because laser welding process parameters of adding powder are the same as that of no powder, moreover, there are no change for laser wavelength, thus laser energy absorption rate depends upon the resistivity. In the case of no powder, laser energy absorption for the lower materials is