Materials and Design 109 (2016) 146–152

Contents lists available at ScienceDirect

Materials and Design

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

Effect of axial magnetic field in the laser beam welding of stainless steel to aluminum alloy

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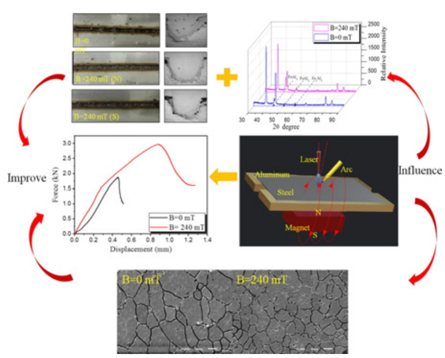
HIGHLIGHTS

- Magnetic field assisted fiber laser welding was applied to join steel to aluminum for the first time.
- The grain refining effect of the magnetic field during the laser welding was studied.
- Suppression of the diffusion by the magnetic field was confirmed during the welding of steel and aluminum.
- Mechanical properties improved with the magnetic field perpendicular to the welding direction.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 6 November 2015
Received in revised form 6 July 2016
Accepted 13 July 2016
Available online 15 July 2016

Keywords:
Magnetic field
Laser welding
Stainless steel
Aluminum
Intermetallic compounds

ABSTRACT

External magnetic field has been favored in the welding, due to the beneficial effects on the weld pool dynamics. The overlapping welding in a keyhole mode with a magnetic field perpendicular to the welding direction was carried out between stainless steel 301 and aluminum alloy 5754 in this study. The results indicated that the application of the magnetic field can modify the weld bead appearance and microstructure of the weld by the Lorenz force and thermoelectric magnetic force induced in the molten pool. Furthermore, the reaction area between steel/Al decreased due to the diffusion of the Al atoms was suppressed, consequently reducing the microhardness and then strengthening the transverse tensile force by 54.6% from 1.81 kN to 2.91 kN.

1. Introduction

As the pursuit for high efficiency and low energy grows rapidly in the manufacturing industry, hybrid structures of stainless steel and aluminum alloy have been increasingly applied in automotive, spacecraft and steamship to obtain light weight with high stiffness [1]. However, joining of these two materials is a great challenge because of the large differences such as melting points, thermal conductivity, thermal expansion coefficients and electrical resistivity, nearly zero solid solubility of Fe in Al which lead to the formation of brittle intermetallic compounds (IMCs) like $FeAl_3$, Fe_2Al_5 and $FeAl_2$ [2]. All of these result in a poor metallurgical compatibility of these dissimilar metals. Therefore, extensive efforts have been made to join aluminum alloy and stainless steel together such as solid state joining [3,4,5], fusion welding [6], welding-brazing [7,8]. The amount of the IMCs is one of the determining

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http://dx.doi.org/10.1016/j.matdes.2016.07.064

factors for the connection reliability of the dissimilar metals [9]. However, some of those processes could not provide a joint with fine mechanical property for the generation of excessive IMCs, while others need rather high pressure or expensive equipments. Therefore, an economy and high efficiency method which can suppress the growth of the IMCs is extremely urgent to be proposed.

Laser welding has been widely used in welding for the localized energy input, short process time which contribute to the inhabitation of the Fe—Al reaction [10–11]. In order to utilize and maximize the advantages of laser welding in dissimilar metals joining, various of process methods had been adopted. A special technique was designed in which a rolling system was combined to the laser [12–14]. The laser heated the substrate and a pressure was immediately applied on the soft metal using the rolling system. Recently, it was reported that preplacing a variety of single and multi-components activating fluxes on the surface of the metal before laser welding could improve the strength of the steel/Al joints [1]. The application of magnetic field in presence of electrically conducting liquids is widely used as it has a distinct effect on the dynamics of the flow behavior [15]. M. Bachmann et al. [16–18] had conducted a series of work investigating the positive influence of externally applied AC and DC magnetic fields on the weld quality during the welding of stainless steel and aluminum respectively. Moreover, it was reported that the magnetic field may have an effect on the diffusion of the atoms in the materials, which lead to the change in phase transformation, grain growth and recrystallization [19]. Zhaojing Yuan [20] used a diffusion couple technique to investigate the diffusion behavior of aluminum in Ni—Al alloy under a magnetic field. The results revealed that the diffusion of aluminum in the direction parallel to the magnetic field was suppressed and the decreasing of frequency factor was regarded as the cause factor. So a method which combines the superiority of the laser and the effect characteristics of the magnetic field has a great potential in the strengthening of steel/Al joints.

Previous studies mainly focused on the application of magnetic field on the joining of homogenous metals by laser welding, little attention was paid to the effects on the dissimilar metals. In this study, a configuration consisted of a fiber laser and a permanent magnet was utilized in the welding of steel/Al for the first time. The external steady magnetic field is utilized in steel/Al laser welding process perpendicularly to the welding direction. The macroscopic weld appearance and the joint microstructure were observed and compared with the weld without a magnetic field. Mechanical properties were thoroughly investigated to discuss the function of the magnetic field in the laser welding of the steel/Al.

2. Materials and methods

The materials used in the experiments were 2 mm thick 301 stainless steel sheet and 2 mm thick aluminum 5754 alloy (Al—Mg) sheet. The 2 mm thickness is of a wide application for the flexibility and formability in the assembling of the automotive. The chemical composition and mechanical properties of the materials are given in Tables 1 and 2 respectively. There were significant differences between these two metals. As the thermal conductivity of 5754 alloy was nearly one hundred times larger than the stainless steel, the steel was placed upon the 5754 alloy as Fig. 1 so as to decrease the energy loss during the welding. Also, as the density of steel is much bigger than the Al alloy, it benefits for the fusion of steel into Al alloy.

Table 1
The chemical composition of the welding materials (in wt%).

Elements	SUS301	5754 alloy
Fe	balance	0.37
Al	–	balance
Mn	Max 2.0	0.25
Mg	–	3.2
Ni	6.0–8.0	0.006
Cr	17.0	0.08
Si	Max 1.0	0.12
C	Max 0.1 5	–

Table 2
The physical and thermal properties of welding materials.

properties	SUS301	5754 alloy
Material density(g/cm^3)	7.89	2.69
Coefficient of expansion(1/K)	16.6×10^{-6}	24×10^{-6}
Melting temperature(°C)	1350	660
Thermal conductivity(W/mK)	16.3	217.7
Ultimate tensile strength(MPa)	Min 520	165–265
Hardness	Max 200	74

The schematic illustration of the set up was shown in Fig. 1. A permanent magnet was assembled on the foundation plate depending on the interaction force between the magnet and the steel plate. An argon nozzle was put 45°from the laser probe in order to protect the substrate from oxidation. The experiments were conducted according to the parameters in Table 3. The intensity of the magnetic field was set as the single variable parameter while the others were kept unchanged. The experiment groups were divided into two groups according to the polarity of the magnetic. (N) means the N pole was put upwards. The magnetic induction lines starting from the N pole come back into the S pole. As the size of the molten pool was so small comparing with the area of the magnetic field, the distribution of the magnetic induction lines along the welding line could be supposed to be homogeneous and pass through the molten pool vertically. The intensity of magnetic field along the weld bead was tested via a digital gauss meter before welding.

The samples were polished and degreased with acetone before welding because the surfaces were easily to be oxidized and acidized by the environment. The samples were then polished and etched by Keller reagent after welding. A three-dimensional stereoscopic microscope and a scanning electron microscope (SEM) were applied to observe the weld bead and the microstructure of the weld. X-Ray Diffraction (XRD) and Energy Dispersive Spectrometer (EDS) were used to analysis the chemical element distribution and the phases in the joints. Microhardness and transverse tensile shear strength tests were conducted to measure the mechanical properties of the joints.

3. Results and discussion

3.1. Analysis of morphological and metallurgical characteristics of joints

3.1.1. Weld beads appearance

The effect of magnetic field on the surface appearance and cross-section of the Fe—Al interface is shown in Fig. 2. The penetration of steel

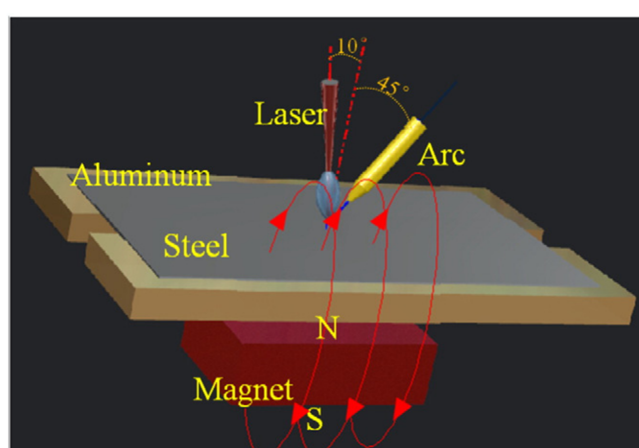

Fig. 1. Schematic of laser welding of steel and aluminum.