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# Microstructure evolution and phase transition at the interface of steel/Al dissimilar alloys during Nd: YAG laser welding

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ABSTRACT

In this paper, we conducted fiber laser welding of steel/Al dissimilar alloys. The microstructural evolution and phase transition at the interface of laser welded joints were carefully investigated using an optical microscope, scanning electron microscope, energy diffraction spectrum and X-ray diffractometer. The forming mechanism of cracking was also studied by experimental and simulated methods. We determined that microstructural segregation at the interface of steel-Al joints was closely associated with the Al content in the steel side. Multiple Fe-Al intermetallic compounds (IMCs), such as $Fe_2Al_5$, $FeAl_3$ and FeAl, were produced at the interface. Formation of these IMCs can improve the hardness of the interface layer dramatically. The continuous or semi-continuous distribution of Fe-Al IMCs with brittleness decreased the plastic and ductility of material itself, which greatly increased the susceptibility of solidification cracking in the fusion zone. The temperature gradient in the interface layer was a key factor affecting the residual stress. A method of reducing the heat input was proposed to control the occurrence of cracks. The simulated results were consistent with the experimental results, which proved the correctness and feasibility of the method.



## 1. Introduction

We have observed growing interest for lightweight to achieve energy saving and emission reduction in many industrial applications, such as vehicles, airplane and spacecraft [1]. Among various lightweight methods, the hybrid structures of aluminum and steel have attracted much attention in that they can reduce body weight and assure the driving smoothness of vehicle. However, joining of aluminum alloy to steel is rather difficult due to their disparity in thermo physical properties, as well as fast formation of detrimental Fe-Al intermetallic compounds (IMCs) [2]. The IMCs tend to reduce significantly the ductility of joint and increase the cracking susceptibility [3], leading to compromising the safety of certain products in service. In consequence, intensive efforts have been made to join steel and aluminum alloy together, such as cold metal transfer welding [4], friction stir welding [5], MIG arc brazing-fusion welding [6] and explosive welding [7]. The heat source is very difficult to control accurately, so a large number of intermetallic compounds are produced at the interface during the welding process.

With improving laser output power and beam quality, especially in controlling accurately heat input during the welding process, laser welding is considered to be a desirable method for joining Fe/Al dissimilar alloys. Jin et al. [8] demonstrated that Al-rich Fe–Al IMCs was harder in a lap joint configuration joint, which could initiate microcracks and deteriorate the mechanical properties of joint. Zhou et al. [9] found that during laser lap welding, an addition of Pb foil can reduce the layer thickness of IMCs and inhibit the formation of IMCs due to the precipitation of copper $Mg_2Pb$ phase. Sierra et al. [10] proved that formation of IMCs in a steel/aluminum overlap joint was inhibited via controlling steel penetration in aluminum. They also indicated that the critical penetration depth was around 500 μm. Liu et al. [11] demonstrated that the intermetallic compound ($Fe_2Al_5Zn_{0.4}$) at the steel/filler layer interface was a ductile and tough phase, which can prevent effectively the occurrence of cracks in the interfacial reactive layer. Ma et al. [12] confirmed that the thickness of the Al-rich IMCs could be controlled at about 5 μm under optimal parameters and the presence the IMCs could improve the strength of the galvanized steel to aluminum lap joints. Qin et al. [13] conducted

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laser + MIG arc hybrid brazing-fusion welding, and discovered a zinc-rich zone at fusion weld toe and Fe–Al intermetallic compounds (IMCs) layer of 2–4 μm in thickness in the brazed seam involving $FeAl_2$, $Fe_2Al_5$ and $Fe_4Al_{13}$. These reports focused on the relationship between Fe–Al intermetallic compounds and mechanical properties of joints. Extensive efforts were tried to control the thickness of Fe-Al IMCs so as to improve the joint performance. In addition, the joint performance can be also affected by the microstructure at the interface of the steel/Al joint.

The idea of this present research is to study the microstructural evolution and phase transition at the interface of laser welded joints in steel/Al dissimilar alloys. The forming mechanism of cracking in the interface layer was carefully investigated by experimental and simulated methods. A method was proposed to suppress the cracks during laser welding steel/Al dissimilar alloys, which is helpful to improve the joint performance and expand the application of dissimilar alloys joint in industrial manufacturing.

## 2. Materials and methods

The materials used in this study were 1 mm thick galvanized steel sheet and 1 mm thick aluminum 6061 alloy sheet. The chemical composition (in wt.%) of base material is given in Table 1.

The experimental laser is an YtterbiumFiber laser, YLR-4000. The main technical parameters of this laser are as follows: lens focal length of 250 mm, focal point diameter of 0.5 mm, emission wave length of 1.07 μm and normal output power of 4 kW. The experimental plates of dimension 200 × 150 × 1 mm were subjected to a series of physical and chemical cleaning prior to laser welding. The schematic illustration of the setup is demonstrated in Fig. 1. The steel plate was placed upon the 6061 alloy plate, aiming at reducing the energy loss and favoring the fusion of steel into aluminum alloy during the process of laser welding. The lap length between steel and aluminum plate was 40 mm. To better the weld appearance, argon gas which acted as a shielding gas, was delivered to the weld surface via a nozzle. In addition, an angle α (referred to 8–15°) between the welding optics and the vertical plane of samples was appropriately designed to prevent laser high reflection from destroying the lens during the welding process.

The cross-section of laser welded specimens was processed along the welding direction using a line cut machine. Specimens for metallographic observations were mechanically polished and then etched with solutions involving 4% $HNO_3$ mixed with alcohol and Keller reagent, respectively. The tested three specimens with same welding parameters were applied to evaluate the susceptibility to weld cracking. Microstructural features and compositions were detected using a Sirion 200 scanning electron microscope equipped with EDAX. The microhardness distribution of specimens and XRD analysis were conducted to investigate the microstructure evolution at the interface.

## 3. Results and discussion

### 3.1. Microstructure of the joint

Fig. 2 shows the microstructure of a welded joint under an optical microscope. Significant differences were observed at the interface of the joint. Many welding defects, such as spatter and loss of molten material, were obviously observed on the surface of the samples. Those defects were closely correlated with the laser welding stability [14,15].

Compared with the microstructure at the FZ (Fusion Zone)/Al interface, it seemed relatively small at the FZ/Fe interface. The occurrence of segregated structures was likely to depend on the temperature gradient at the interface. Generally, a larger temperature gradient can lead to producing coarse columnar crystals, which deteriorated the performance of joints. Further observation revealed that a large amount of block or banded structures were formed at the FZ/Al interface. The possible phases of those

**Table 1**
Chemical compositions of specimen (wt.%).

| Materials | C | Si | Mn | P | S | Alt | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| DP590 | ≤0.18 | ≤0.8 | ≤2.2 | ≤0.035 | ≤0.03 | ≥0.02 | | | | |
| Materials | Fe | Si | Cu | Mn | Mg | Cr | Zn | Ti | Trace element | Al |
| 6061 | 0.7 | 0.4–0.8 | 0.15–0.4 | 0.15 | 0.8–0.12 | 0.04–0.35 | 0.25 | 0.15 | 0.15 | Bal |

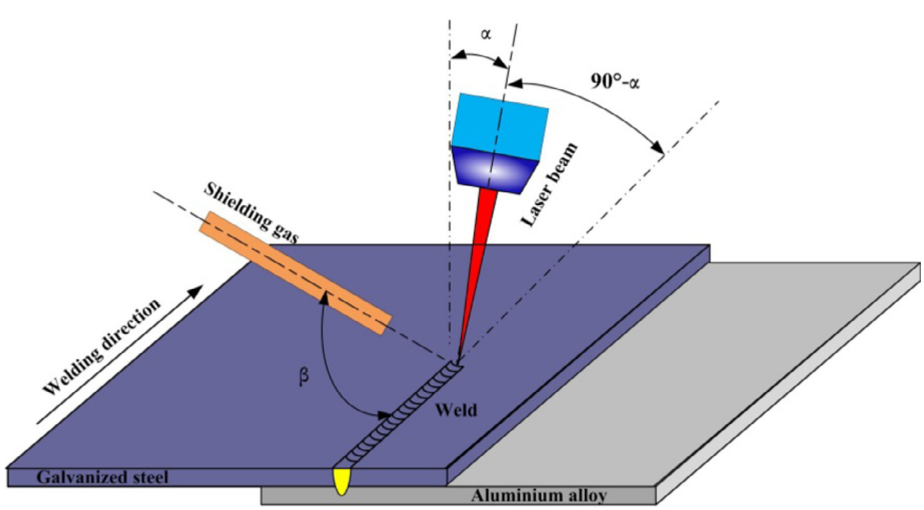


**Fig. 1.** Schematic diagram of laser welding steel and aluminum.