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Analysis of process parameters effects on friction stir welding of dissimilar aluminum alloy to advanced high strength steel

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ABSTRACT

Thin sheets of aluminum alloy 6061-T6 and one type of Advanced high strength steel, transformation induced plasticity (TRIP) steel have been successfully butt joined using friction stir welding (FSW) technique. The maximum ultimate tensile strength can reach 85% of the base aluminum alloy. Intermetallic compound (IMC) layer of FeAl or Fe_3Al with thickness of less than 1 μm was formed at the Al–Fe interface in the advancing side, which can actually contribute to the joint strength. Tensile tests and scanning electron microscopy (SEM) results indicate that the weld nugget can be considered as aluminum matrix composite, which is enhanced by dispersed sheared-off steel fragments encompassed by a thin intermetallic layer or simply intermetallic particles. Effects of process parameters on the joint microstructure evolution were analyzed based on mechanical welding force and temperature that have been measured during the welding process.

1. Introduction

Growing concerns on energy saving and environmental preservations increase the demand for lightweight vehicles. Considerable volumes of advanced high strength steel sheet have been applied into automotive parts in order to reach the objective of both weight reduction and crashworthiness enhancement. However, further weight reduction of 30% or more is hardly achievable with exclusive dependence on the use of thinner steel sheets. Multi-material vehicle structures is an efficient countermeasure against this problem [1], which necessitates the development of reliable and cost-effective dissimilar material joining technique. One of the desired pairs is aluminum alloy and advanced high strength steel, which is highly difficult to be welded together due to their differences in physical and mechanical properties as well as the formation of large amount of brittle intermetallic compounds (IMC) using traditional fusion welding techniques [2–6].

Friction stir welding (FSW), which was first developed by The Welding Institute (TWI) in 1991 [7], has a solid-state nature and therefore exhibits certain advantages over traditional fusion welding methods. First, it can significantly avoid solidification related problems, such as oxidization, shrinkage, porosity, and hydrogen solubility [8]. Second, the associated low heat input can effectively inhibit intermetallic compound (IMC) layer formation, which makes it a promising solution for dissimilar material joining. Several studies have been carried out on FSW of aluminum alloy to steel sheets. Uzun et al. [9] reported the joint strength between 304 stainless steel and Al 6013-T4 with thickness of 4 mm can reach approximately 70% of the base aluminum alloy. Ghosh et al. [10] did FSW of pure Al to 304 stainless steel and the ultimate tensile strength can achieve 82% of Al. Presence of Fe_3Al was reported. Besides, equiaxed and finer grains exist in the stirring zone, which indicate the involved dynamic recrystallization process. Tanaka et al. [11] welded Al7075-T6 to mild steel of the thickness of 3 mm. Tool rotational speed varies from 400 to 1200 rpm under the welding speed of 100 mm/min. The highest tensile strength they can achieve is 333 MPa, which is about 60% of the base aluminum alloy. Moreover, they reported an exponentially increasing relation- ship between the interface strength and the reducing thickness of IMC layer, which has the composition of $FeAl_3$. Lee et al. [12] did experiments on FW of Al6056-T4 to 304 stainless steel with thickness of 4 mm under the rotational speed of 800 rpm and welding speed of 80 mm/min. The thin intermetallic compound layer of 250 nm thickness was analyzed through transmission electron microscopy (TEM) and identified to be $FeAl_4$. Chen and Kovacevic [13] joined Al6061 to AISI 1018 steel sheet with the thickness of 6 mm. Local melting of Aluminum was observed and shear-off steel platelets encompassed by IMC layers of Fe_4Al_{13} and Fe_2Al_5 existed in the weld nugget. Locally partial molten Aluminum was again reported by Jiang and Kovacevic [14] when they did study on the same pair of materials with the same thickness.

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Intermetallic compounds are found not only in the segregated steel clusters inside the weld nugget but also along the interface between base steel and the nugget. Their constitutions were identified to be Fe_2Al_5 and Fe_4Al_{13}. The severity of IMC reaction depends on locations and more steel is consumed at a distance closer to Aluminum alloy. Movahedi et al. [5] did friction stir lap joint between Al5083 and St-12 mild steel. They found that an intermetallic compound layer with a thickness of less than 2μm will not degrade joint quality. Similar results were suggested by Lee et al. [15] and they reported that 2um IMC layers with the composition of Fe_3Al, Fe_4Al_{13} can contribute to the joint strength. Yilmaz et al. [16] also reported that the Al/Fe interface with a layer of IMC is important to the weld strength but cracks can easily initiate and propagate if the IMC layer is too thick. This statement was further verified by Bozzi et al. [17] when they studied friction stir spot welding of Al6016 to IF-steel and reported that fractures are likely to be generated through the hard IMC tangles when the thickness of IMC layer is larger than 8 μm. In their studies, $FeAl_2$, Fe_2Al_5 and $FeAl_3$ were observed at different positions using TEM. Chen [18] did process parameter study of FSW on Al6061-T651 aluminum alloy to SS400 steel with the thickness of 6 mm. They indicated that rotational and traverse speed are relatively significant FSW process parameters compared to the tool tilt angle or pin diameter. Furthermore, lower rotational speed and transverse speed can result in higher impact values of joint strength. Their maximum tensile strength can reach 76% of the base Al alloy. Kimapong and Watanabe [19] did FSW lap joint on A5083 to SS400 mild steel and reported a maximum shear strength of about 77% of the aluminum base material. FeAl, $FeAl_3$ and Fe_2Al_5 were found in the interface corresponding to different tool tilt angles. Chen et al. [20] suggested the Zn coating on steel could improve the weldability of Al and steel through promoting the formation of Al–Zn low melting point eutectic structure. They also reported in another study [21] on FSW lap joint that the thickness of IMC layer increases from 7.7μm to 58.1 μm with decreasing welding speed, which significantly affect the strength of the joint. The composition was identified to be mainly Fe_2Al_5 and Fe_4Al_{13}. Watanabe et al. [22] joined SS400 mild steel to A5083 Al alloy with the thickness of 2 mm. The maximum tensile strength they have obtained is about 86% of the base Aluminum alloy when 10% of the cross-sectional area of pin was placed in the steel side. The fracture path was along the interface between Al matrix and Fe fragments. IMCs with the composition of FeAl and $FeAl_3$ exist at the upper region of the weld interface.

However, all the aforementioned studies selected either mild steel or austenite stainless steel, both of which have a relatively low yield strength. So far, few open literatures have reported FSW of aluminum alloy to advanced high strength steels (AHSS), which is more desirable in lightweight vehicle structures. AHSS has a much higher mechanical strength and work hardening rate, which is accomplished by their multiple phase microstructure. AHSS consists of four subcategories, i.e. dual phase (DP) steel, transformation induced plasticity (TRIP) steel, complex phase (CP) steel and martensitic steel (MART) [23]. In this work, feasibility of using FSW to join Al 6061 and TRIP 780/800 steel together was investigated and effects of different process parameters were analyzed. Microstructure evolution of the weld was related to mechanical welding forces exerted on the FSW tool and temperature distributions on the workpiece for a thorough understanding of the underlying mechanism.

2. Experiment

Fig. 1(a) shows a schematically axonometric view of the whole FSW experimental arrangements and Fig. 1(b) shows a more detailed cross-sectional view perpendicular to the weld line. TRIP 780/800 steel sheets with the thickness of 1.4 mm were provided by the United States Steel Corporation. Its yield strength (YS) is 780 MPa, which is more than three times of that of Al6061. According to Watanabe et al. [22], steel should be put in the advancing side for admissible joining configurations. The thickness of aluminum alloy Al6061-T6511 is 1.5 mm and its chemical compositions and mechanical properties are listed in Table 1, where UTS stands for ultimate tensile strength.

Blue[1] lines in Fig. 1 indicate the contour of the FSW tool, which consists of a conically tapered non-threaded pin. Specific dimensions of the tool are shown in Fig. 2. To avoid overheating of aluminum, the FSW tool should be shifted towards aluminum. However, partial of the pin need to remain in the steel side to actually stir both materials together. The parameter of tool offset is therefore introduced here as the distance between the tool axis and the faying surface of the two materials. Larger tool offset means the tool is more into aluminum. Since part of the FSW tool will be immersed in the steel side and subjected to severe frictional conditions, refractory materials such as tungsten carbide [24–27], tungsten–rhenium [28], Si_3N_4 [29] and polycrystalline cubic boron nitride (PCBN) [30–32] are required for the tool. In our study, tungsten carbide with 10% cobalt content was selected for its good wear resistance and much lower cost compared with PCBN.

Below the workpieces is a replaceable backing plate made of mild steel, where four holes with diameter of 1 mm were drilled for mounting thermocouples. Type K thermocouples, shown as red spots in Fig. 1, are located symmetrically to the weld line and measure the temperature of the workpiece back surface at distances of 1 mm and 5 mm away from the abutting edge.

The workpiece and replaceable backing plate were assembled onto a specially designed fixture, which was further mounted onto a dynamometer (Kistler 9255B). The dynamometer was used to measure the mechanical welding force in both vertical direction F_z and the direction along joint line F_x. All FSW experiments were performed on the high stiffness M.S. Machining Center under displacement control. Two levels of rotational speed, 1200 rpm and 1800 rpm were investigated under three levels of welding speed and two levels of tool offset. As shown in Table 2, a total of 12 welding conditions were carried out in this study and each condition was repeated three times for average and error bar calculation. R, FT and Offset are abbreviations for rotational speed, welding speed and tool offset respectively, which are frequently referred to in the figures shown in following sessions.

Microstructural analysis using both optical microscopy (OM) and Scanning Electron Microscopy (SEM) were performed on the joint cross sections perpendicular to the weld line. Composition of the interface layer was analyzed using X-ray diffraction (XRD) technique. Tensile specimens perpendicular to the weld line were prepared according to the ASTM: E8 standard. Their specific shape and dimensions are shown in Fig. 3. Thickness of the tensile specimens is the same as the original workpiece but with a transition thickness in the weld area, which was located almost right in the center. All the tensile tests were conducted on the MTS Insight 10 tensile machine at a strain rate of 10^{-3}.

3. Results and discussion

3.1. Microstructure overview and material flow visualization

A typical optical macroimage of the joint cross section perpendicular to the weldline is shown in Fig. 4, which reveals a good

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[1] For interpretation of color in Fig. 1, the reader is referred to the web version of this article.