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Technical Paper

Effects of preheating treatment on temperature distribution and material flow of aluminum alloy and steel friction stir welds

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ABSTRACT

Material flow and temperature distribution during welding are important factors that affect the properties of friction stir welding (FSW) joints. The scope of this investigation is to evaluate the effect of preheating treatment on the temperature distribution and material flow of aluminum alloy and steel joints produced by FSW. In this investigation, the finite volume model of butt FSW was established on basis of the FLUENT software. The flow of material during the FSW was simulated, and the temperature distribution in the FSW process was obtained by experiment and simulation. The effects of preheating treatment on the thermal history, temperature distribution, and material flow during FSW were elucidated in detail. The effects of preheating on the tensile strength and failure modes of the specimens were also discussed. The simulation shows that the preheating treatment increased the peak temperature of the steel, and also reduced the large temperature difference between the steel and the aluminum alloy in the high temperature stage. Simulation results, including temperature distribution and thermal history, were corresponded with the experimental results. The preheating treatment improved the flow velocities of the plastic materials and reduced the difference in flow velocities of the two materials. The preheating treatment could reduce the influence of the difference between the two materials on the forming of the welded joint and improve the property of the welded joint.

1. Introduction

The advanced energy saving and discharge reduction technologies are becoming the focus of the current research to solve the serious problems of environmental pollution and energy consumption. The lightweight design of products is an effective way to reduce energy consumption and environmental pollution. The most effective way to realize the lightweight of products is to replace the steel with aluminum alloy or use aluminum steel composite structure in automobile and aerospace industry [1].

Because of the obvious differences of the physical and chemical properties between aluminum and steel, it seems impossible or very difficult to form a perfect joint between aluminum and steel by using conventional fusion welding methods. At present, the main methods of joining aluminum and steel are laser welding [2], friction welding [3], explosion welding [4], diffusion bonding [5], braze welding [6] and ultrasonic welding [7]. All of the above joining techniques are based on melting the material of the work-piece to be welded, such a problem as the formation of brittle intermetallic compounds (IMCs) is inevitable, and which significantly affected the mechanical properties of the joins. Therefore, it is important to explore new methods to realize the effective join of aluminum and steel.

The formation of IMCs can be inhibited effectively by the low heat input during the friction stir welding (FSW) process, which makes FSW became a promising solution for the welding of aluminum and steel. Several studies have been carried out on the FSW of aluminum alloy to steel.

The effect of welding parameters on the microstructure and properties of the joint has been the focus of the researchers. Butt welding of thin sheets of aluminum alloy 6061-T6 and one type of advanced high strength steel was made by Liu et al. [8] used FSW. They analyzed the effects of process parameters on the joint microstructure evolution based on mechanical welding force and temperature that had been measured during the welding process.

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Table 1
Chemical composition of the base materials (wt%).

Material	C	Si	Mn	S	P	N	O	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
E235A	0.16	0.20	0.61	0.023	0.019	0.0045	0.019	Bal.							
Al6061		0.6						0.35	0.27	0.15	1.0	0.35	0.25	0.08	Bal.

Additionally, Coelho et al. [9] researched the influence of the distinct HSS base material on the joint efficiency. They concluded that the joint efficiency depended foremost on the mechanical properties of the heat and the thermo-mechanical affected zone (TMAZ) of aluminum alloy.

The interface has a significant effect on the strength of the joints. Lee et al. [10] investigated the interfacial reaction in steel-aluminum joints made by FSW. They reported that the reaction layers of friction stir welded joints made from austenitic stainless steel and Al alloy consisted of mixed layers of elongated, ultra-fine grains and the IMC layer. Welding of interstitial free steel and commercial pure aluminum was made by Kundu et al. [11] used FSW. They reported that the Al_3Fe had been observed in the weld interface and the thickness of the different reaction layers was increased with the increase in tool rotational speed. Ramachandran et al. [12] successfully butt joined Aluminum alloy AA5052 and HSLA steel by FSW technique. In their studies, SEM and EDS analysis suggested that in all cases IMC layer was formed at the joint interface and its thickness was critical in the tensile strength of the joint. Bozzi et al. [13] believed that an IMC layer seemed necessary to improve the joint strength, but the thick layer of IMC was detrimental because it significantly deteriorated the bond strength, and they concluded that the type of IMCs depended on welding conditions.

These studies show that the key issue encountered in FSW is the formation of joint structures, which depends on the process related temperature distribution and material flow. In order to change the temperature distribution and the flow of materials in the FSW process, some measures for improvement have been proposed. However, it is very complex and still not fully understood despite many investigations and numerous models. Fei et al. [14] reported that the pre-hole offset distance, the thickness of the IMCs layer and the type of the IMCs were the key factors that affect significantly the tensile strength of the joints in laser-assisted FSW of steel and aluminum alloy. Liu et al. [15] jointed Al 6061 to TRIP 780 steel by electrically assisted FSW, they stated that the enhanced formation of the thin layer of IMCs and micro-interlock features at the Al-Fe interface could be observed in electrically assisted welding conditions, and which was beneficial to the properties of joints. Bang et al. [16] evaluated the potential for using the gas tungsten arc welding (GTAW) assisted hybrid friction stir welding (HFSW) process to join a stainless steel alloy (STS304) to an aluminum alloy (Al6061) in order to improve the weld strength. The results indicated which HFSW that integrates GTAW preheating to FSW was advantageous in joining dissimilar combinations compared to conventional FSW. From the published literature, it is well understood that the preheating treatment not only provides a part of the energy required for the FSW but also changes the structure of the joint. In addition, the preheating treatment can also improve the plasticity and flow velocity of the material. At present, there are few reports about the effect of preheating treatment on the temperature distribution and material flow during FSW process.

In the present paper, arc heating was used to assist the butt FSW process to join AA6061 aluminum alloy to E235A steel. The software FLUENT was employed to understand the temperature distribution and the flow of materials in FSW. The transient temperatures of numerical results were compared with the available experimental data to validate the present simulations. The effects of preheating treatment on the thermal history, temperature distribution, and material flow during FSW were elucidated in detail.

Table 2
Thermo-physical properties of the base materials.

Material	Density ρ ($kg\,m^{-3}$)	Thermal Conductivity λ (W/m·K)	Specific heat capacity C (J/kg K)
E235A	7860	77.5	460
Al6061	2700	167	900

2. Experimental procedures

The thin plates of E235A steel (200mm × 100mm × 2 mm) and AA6061 aluminum alloy (200mm × 100mm × 4 mm) were used in this study. The chemical compositions and the thermo-physical properties of both the materials are given in Tables 1 and 2, respectively.

According to Watanabe et al. [17], steel was placed on the advancing side (AS) for admissible butted welding configurations, as shown in Fig. 1a. The tool was rotated clockwise with respect to the vertical axis. The parameter of tool offset was the distance between the tool axis and the faying surface of the two materials. The tool axis offset used was schematically shown in Fig. 1c.

In order to measure the temperature of the observation point in the FSW process, two holes with diameter of 1 mm were drilled at the bottom of the aluminum plate for mounting thermocouples. Type K thermocouples, shown as the red spots in Fig. 1c, were located symmetrically to the weld line.

FSW equipment was modified by the CNC milling machine, and used the electric arc heater as auxiliary heat source equipment. The fixture used in this study was a simple fixture according to the actual situation of the experiment. The FSW tool was made of tungsten alloy in relative simple geometry. The FSW tool consisted of cylindrical shoulder and a conical pin. The specific dimensions of the tool are shown in Fig. 2.

According to the results of previous experiments, FSW was performed at a tool rotation speed of 1500 rpm (ω) and a weld travel speed of 90 mm/min (u_{weld}). The experiments were carried out on the steel plate under preheating and no preheating conditions. The preheating temperature of the steel plate was 493 K, as shown in Fig. 3.

X-ray diffraction (XRD) measurements were carried out with Phillips X-ray diffractometer (PW-1800model), using Cu-Kα_1 radiation to display the present phases in the welded joints samples (k = 1.541 Å, operating at 40 kV and 20 mA).

The tensile strength of the conventional FSW and the preheated FSW joints were tested. Geometric parameters of the prepared mechanical tensile testing specimens, which extracted from the as-welded steel-to-Al modified butt joints via spark erosion cutting method in the transversal direction of the welding direction, were sketched in Fig. 4. The tensile test was carried out using an Instron 8801 tensile testing machine at a constant speed of 0.5 mm/min. Each result was averaged by no less than three samples. The cross-section macrostructures at the fracture locations were observed using an OM (ZSA403) and fracture surfaces were analyzed using SEM (QUANTA200).

3. Numerical modeling

In this study, the Gambit software was used to build the 3D model and the mesh division. Fluent software was employed to