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Spot friction stir welding of low carbon steel plates preheated by high frequency induction

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ABSTRACT

In this study, high frequency induction heating assisted spot friction stir welding was applied to 1.6 mm thick S12C low carbon steel plates. With the same welding parameter including an applied load of 2500 kg, rotation speed of 800 rpm and dwell time of 2 s, the average grain size in the stir zone slightly increased from 12.9 μm for the welds without preheating to 14.8 μm when 10 s preheating was used. However, larger joint interface was formed within the stir zone of the welds with preheating and therefore the bonding strength can be significantly increased. As a result, the shear tensile load of the joint increased from 8 kN to12.4 kN with preheating and the joint fractured through the plug failure mode rather than interfacial failure mode. It was revealed that the frictional heat generated between the rotating tool and the work-piece can be reduced to obtain sound welds by means of high frequency induction preheating.

1. Introduction

As a relatively new process, spot friction stir welding (FSW) shows great potential to be a replacement for single point joining processes like resistance spot welding (RSW) and rivet technology. From the beginning of its emergence, it has been received considerable attention from the automotive and other industries. It was claimed that for spot FSW the use of energy significantly decreased and the investment cost was about 40% lower due to its minimal equipment requirement [1]. In addition, spot FSW is an environmentally friendly spot welding method due to the absence of any fumes or sparks. Today, a manufactured car requires 2000–5000 spot welds. To increase the fuel economy and improve the vehicle performance in the vehicle industry, spot FSW of light metals, like aluminum alloys, is being adopted by more and more transportation industries. Recently, with the development of high wear-resistance rotating tools, the spot FSW technique has also been expanded to some other materials with higher strength and higher melting point, such as the spot welding of steel [2–4]. For steel, the leading candidate for spot welding is still the RSW method. However, with the growing interest in the application of advanced high strength steels within the automotive architecture, spot FSW offers more reliable qualities than RSW during which the formation of a brittle microstructure occurs due to the high welding temperature and rapid cooling rate [5].

Although the rotating tool has also been developed and can be made of highly durable materials like WC-based alloy [6–8], PCBN [9,10], Si_3N_4 [11–13], Ni alloy [14], Co alloy [15], and Ir alloy [16–18], the wear of the rotating tool is still very severe. Generally a very high load need to be applied on the rotating tool and breaking of the tools often happens. Recently, the high consumption of costly rotating tools is also a big concern and has been investigated by some researchers. For example, Choi et al. [19] studied the wear of the WC-Co tool when subjected to the spot FSW of 0.6 mm thick low carbon steel plates. It was found that extreme wear occurred between the pin center and the edge, which resulted in the variation of the joint strength with the number of welds. The wear of the rotating tool will certainly result in the reduction of the penetration depth during the spot FSW process. Recently, Mitlin et al. studied the relationship between the weld strength and the penetration depth reduction caused by tool wear [20]. It was found that the peak strength could be reached at a certain penetration depth, and then decreased whether the penetration depth became smaller or larger. In addition, the fracture location also changes with the variation in the penetration depth.

With the attempt to extend the tool life and improve the welding efficiency, several preheating methods have been used to introduce more total heat input during the linear FSW process of high melting point metallic materials. For example, the preheating sources can come from the micro-plasma arc [21], electric resistance heat [22], high frequency induction [23], electromagnetic radiation, laser beam, etc. [24,25]. Laser-assisted friction stir welding was invented and patented by Frank Palm in 2001, which has been successfully used in the FSW of nickel alloys and carbon steel

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[26,27]. However, the reports about the use of laser beam as a preheating source during the spot FSW are still very limited.

In this paper, the spot FSW assisted by heat frequency induction was applied to the welding of 1.6 mm thick S12C steel plates, which is thicker than the steel plates generally used for spot welding. Therefore, a higher heat input is required and the wear of the rotating tool is severe during the welding process. After welding, the effect of the preheating on the welding parameter and the final microstructure and mechanical properties of the joints were investigated.

2. Experimental procedure

In this study, commercial carbon steel S12C plates with a thickness of 1.6 mm were subjected to the spot FSW process. The S12C steel has the chemical composition listed in Table 1. The individual sheet is 100 mm in length and 30 mm in width, and two sheets were welded on an overlap area of 30 × 30 mm^2. Prior to welding, the steel sheets were cleaned with acetone to remove any impurities on the surface such as dirt, oil, etc. As for the preheating, high frequency induction heating equipment was installed besides the tool holder of the FSW machine. A water cooled induction coil was used to heat the surface of the work-piece. The entire welding process can be divided into four steps as shown in Fig. 1. First, the rotating tools and induction coil were installed about 5 mm above the sample surface and the induction coil was set exactly above the surface area to be welded. Second, after preheating for a certain time, the coil was quickly removed from the welding area and at the same time, the rotating tool was moved just above the welding area. Thirdly, the rotating tool was plunged into the sample at an applied load and starts to stir the sample. Finally after stirring the sample for a certain time, the rotating tool was retracted from the welds and the welding process was completed. During the welding process, a K-type thermal couple was used to measure the temperature, which was inserted between the two plates about 1 mm away from the rotating tool.

For the welding process, the steel plates were first placed on a steel back plate and clamped tightly. The welding process was then performed using a load-controlled FSW machine. The WC based rotating tool, which had a 12 mm-dia concave shoulder, 4 mm-dia unthreaded probe and 1.9 mm probe length, was used during all the welding processes. After several trials, a rotation speed of 800 rpm and an applied load of 2500 kg were used to investigate the effect of preheating by high frequency induction. The frequency used in the induction heating system was 20 kHz and the coil current was 400 A. The selected preheating periods were 5 s and 10 s. The time period for the stir welding by the rotating tool was 2 s.

After welding, optical microscopy (OM) and electron backscattered diffraction (EBSD) were used to characterize the microstructure of the joints. The specimens for the OM observations were first mechanically polished with abrasive paper up to 1000 grit followed by a final polish with 1 μm Al_2O_3 suspensions. The polished steel specimens were then chemically etched with 4% Nital solution. The OM observations were carried out using an Olympus BX51M microscope. The EBSD measurements were carried out using a JEM-7001FA field emission scanning electron microscope (FE-SEM) with a TSL orientation imaging system. The microstructures in the center of the stir zone after the second step as well

Table 1
Chemical composition of S12C steel.

S12C	C	Mn	P	S	Fe
Mass%	0.12	0.29	0.008	0.02	Bal.

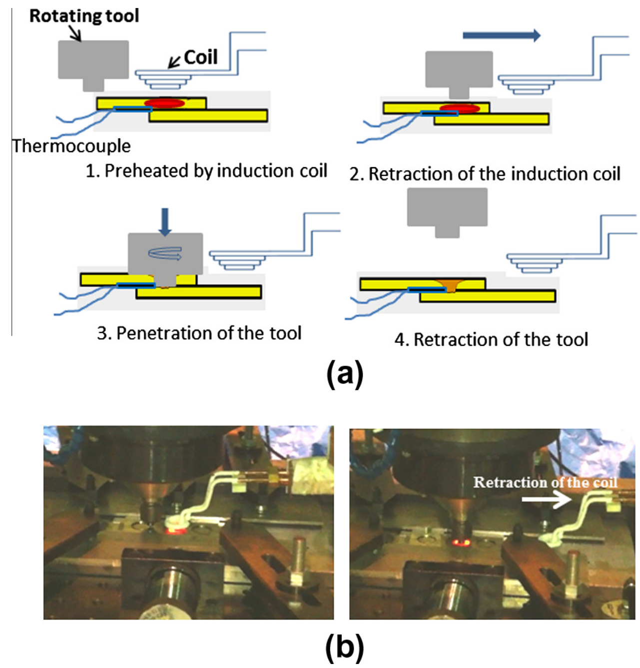

Fig. 1. (a) Outline showing the principle of the preheat-assisted spot FSW process and (b) photos taken during the spot FSW process.

as the base metal were also characterized by transmission electronic microscopy (TEM). For the TEM sample preparation, thin sheets were first cut at the desired locations and then mechanically polished to 100 μm. The thin polished sheets were finally twin-jet electro-polished to form an electron beam transparent thin film using a solution of $HClO_4$:CH_3COOH = 1:9 at 30 V and 10 °C. The thin films were observed using a JEOL 2100F TEM at 200 kV. The Vickers hardness tests on the cross-sectional plane of the welds were carried out using an Akashi AAV-500 Vickers hardness testing machine according to ASTM:E384-11. The shear tensile tests of the welds were carried out using an Instron-type testing machine with a crosshead speed of 1 mm/min, according to the JIS Z 3136:1999 standard [28].

3. Experimental results and discussion

3.1. Thermal history

Fig. 2 shows the effect of preheating on the temperature profile during the spot FSW process. Generally the temperature profile can be divided into three stages, namely, ① the preheating stage; ② the tool penetrating stage, and ③ the welding stage. For the welding without preheating as shown in Fig. 2(a), the temperature profile only contains the last two stages. The temperature of the materials started to increase when the tool touched the steel plate and gradually increased during the welding process. Due to the low thermal conductivity of carbon steel, the temperature was not constant during the 2 s welding period but continuously increased untill it finally reached a peak temperature of about 700 °C at the end of the welding process. The temperature then immediately dropped after the retraction of the rotating tool from the workpiece. As for the spot FSW with preheating, Fig. 2(b) and (c) show the temperature changes with a preheating of 5 s and 10 s, respectively. The temperature started to increase during the preheating period. After preheating for 5 s, the temperature reached about 550 °C. When preheating for 10 s, the temperature reached about 950 °C. There was then a temperature drop after preheating due