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Effect of Rotation Rate on Microstructure and Mechanical Properties of Friction Stir Spot Welded DP780 Steel

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DP780 steel sheets consisting of ferrite and martensite were successfully friction stir spot welded (FSSW) at the rotation rates of 500 to 1500 r/min using a W-Re alloy tool. The effect of rotation rate on microstructure and mechanical properties of the FSSW DP780 was investigated. The peak temperatures in the welds at various rotation rates were identified to be above A_3 temperature. FSSW caused the dynamic recrystallization in the stir zone (SZ), thereby producing the fine equiaxed grain structures. At the higher rotation rates of ≥1000 r/min, a full martensitic structure was observed throughout the SZs, whereas at the lower rotation rate of 500 r/min, the SZ consisted of a fine dual phase structure of ferrite and martensite due to the action of deformation induced ferrite transformation. The maximum average failure load as high as 18.2 kN was obtained at the rotation rate of 1000 r/min and the fracture occurred at the thinned upper sheet.

1. Introduction

It is widely accepted that in the automotive industry, the reduction in the vehicle weight can decrease greatly the energy consumption and carbon emission. Recently, the application of advanced high strength steels (AHSSs) – auto-structural materials having great potential – in automotive fabrication has been attempted, owing to their high strength, sound formability and perfect crash performance[1]. The dual phase (DP) steel containing both ductile ferrite matrix and hard martensite is a most typical AHSS. However, for the conventional resistance spot welding (RSW) applied extensively in the automotive industry, welds of the DP steels with excellent strength and toughness are produced with difficulty. This is because the relatively coarse and hard quenched microstructures and the solidification defects such as crack and porosity are formed easily in the fusion zone of the welds due to the extremely high cooling rate of electrodes during RSW[2,3].

Based on the fundamental principle of friction stir welding (FSW)[4], a new spot welding technology called friction stir spot welding (FSSW) has been developed[5]. Because of the solid-state nature of the FSSW process, the peak temperature during the FSSW thermal cycle is remarkably lower than the melting point of metals, thereby restricting the formation of the coarse grains and the detrimental solidification defects. Therefore, the higher strength and toughness would be yielded in the FSSW joints. In the past few years, a number of FSSW efforts were focused on Al alloys[6–8], and an attempt has been made by MAZDA Corporation to FSSW Al alloy rear door[9]. However, only relatively limited studies on FSSW DP series steels were reported[10–16].

Khan et al.[10] and Ohashi[11] reported that at the rotation rate of 3000 r/min, FSSW DP600 steels were conducted with tools made from W-Re alloy and Si_3N_4 ceramics, respectively, and a full martensitic phase was observed in the stir zones (SZs). On the other hand, Feng et al.[12] noted that at a rotation rate of 1500 r/min, the SZ consisting of bainite and acicular ferrite was made in the FSSW DP600 steel using a PCBN tool. Clearly, it is hard to evaluate the effect of the welding parameters on microstructural evolution and mechanical properties of the welded joints, because different welding tools were used in studies on FSSW DP steels. Therefore, in the present work, the DP780 sheets were subjected to FSSW at a wide rotation rate ranging from 500 to 1500 r/min using W-Re alloy tool. The influence of rotation rate on microstructural evolution and mechanical properties during the FSSW process was discussed in detail.

2. Experimental

Uncoated DP780 sheets of 1.5 mm in thickness, 100 mm in length and 30 mm in width with a chemical composition of 0.15C–1.8Mn–

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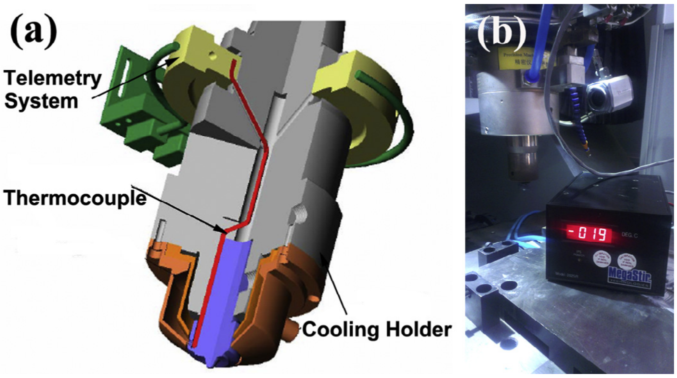

Fig. 1. Telemetry measurement system and liquid cooling holder.

0.35Si–0.6Cr–Fe (wt%) were used in FSSW. The carbon equivalent (CE) of DP780 was calculated as ~0.57 (wt%) by means of the following equation: CE = C + Mn/6 + (Ni + Cu)/15 + (Cr + Mo + V)/5. FSSW was conducted at the rotation rates of 500, 1000 and 1500 r/min with a constant welding time of 4 s and a fixed welding load of 20 kN. A W–25Re (wt%) tool consisting of a concave shoulder of 10 mm diameter and a pin of 4 mm diameter and 1.8 mm length, and a liquid cooling holder (MegaStir Technologies, USA) maintaining a temperature of ~20 °C were adopted in FSSW as shown in Fig. 1. A telemetry measurement system (MegaStir Technologies, USA) placed on the cooling holder was used to measure the peak temperatures at a location 1 mm from the shoulder via a K-type thermocouple (Fig. 1). The equilibrium temperatures for the DP780 steel at the A_1 and A_3 points were calculated by Thermo-Calc software. The FSSW samples were sectioned across the center of the keyhole, polished and then etched with a solution of 95 mL ethanol and 5 mL nitric acid. Microstructures were characterized by optical microscopy (OM) and scanning electron microscopy (SEM), and the phase fractions were analyzed by Scion software. Element distributions were measured by JEOL5853-type electron probe microscopic analyses (EPMA). Electron backscatter diffraction (EBSD) orientation maps were obtained by using the ZEISS SUPRA 55. The Vickers hardness values were measured by Future-Tech machine with a load of 200 g for 10 s. Three tensile shear samples produced by FSSW at each rotation rate were used to evaluate the average shear failure loads using Instron testing machine at a constant strain rate of 1×10^{-3} s^{-1}.

3. Results and Discussion

3.1. *Influence of rotation rates on microstructure*

Fig. 2shows the cross-sectional macrographs of the FSSW DP780 joints made at various rotation rates, i.e. various heat input conditions. No defect was detected in these FSSW joints. This means that the sound joints could be achieved under a wide heat input range of 500 to 1500 r/min, showing sufficient plastic flow during the FSSW DP780 process. All the welds exhibit a typical basin-shaped outline with a keyhole. As reported previously in the FSSW DP steel joints[10,11], the FSSW DP780 joint was classified as three zones, the SZ, heat affected zone (HAZ) consisting of inner HAZ (IHAZ) and outer HAZ (OHAZ), and parent material (PM), as shown in Fig. 2(a). Furthermore, it is indicated that increasing the rotation rate creates the increase in the bonding interface width "*a*" and the reduction in the thickness "*b*" of the upper sheet. This is because with increasing rotation rate, the enhanced heat input facilitated both the plastic flow and heating diffusion between the upper and lower sheets, and reduced the deformation resistance of the upper sheet. However, both the bonding interface width and the thickness of the upper sheet would exert a significant effect on mechanical properties of the FSSW joints.

Microstructural characteristics of the PM, HAZ and SZ of the FSSW DP780 joints at the rotation rate of 1000 r/min are shown in Fig. 3. The PM is characterized by bulky ferrite and fine martensite mainly distributed near ferrite boundaries (Fig. 3(a)). The OHAZ and the IHAZ exhibit the dual phase of ferrite and martensite, and the single martensite phase, respectively. In fact, various microstructural characteristics in the two sub-regions of the HAZ were related to the different peak temperatures experienced during the FSSW thermal cycle. The peak temperature of the OHAZ fell in the dual phase field of α and γ, thereby resulting in the partial austenitization of ferrite in the PM on heating during FSSW. Therefore, the dual phase of ferrite and martensite was achieved on cooling after FSSW due to the higher hardenability of DP780 with a CE of 0.57 (wt%). For comparison, in the IHAZ where a peak temperature above A_3 occurred, the original dual phase structure was fully-austenitized, and then was transformed into full martensite phase on cooling after FSSW.

To explore the microstructural evolution of the SZs at various rotation rates, it is quite necessary to obtain the peak temperature during FSSW. The telemetry measurement system presented in Fig. 1(b) reveals that at the rotation rates of 500, 1000 and 1500 r/min, the peak temperatures adjacent to the shoulder are 868, 945 and 1040 °C, respectively. However, according to the temperature distribution during FSSW, the peak temperatures within SZs should exceed those measured near the shoulder. Through the Thermal–Calc software, the temperatures of A_1 and A_3 for the DP780 steel used in FSSW were determined to be 682 and 815 °C, respectively. Clearly, the peak temperatures in the SZs at various rotation rates surpassed A_3 temperature. Fig. 3(d) shows that the SZ at 1000 r/min is composed of finer martensite phase than that in the IHAZ. At the rotation rate of 1000 r/min the FSSW causes a high peak temperature above A_3 and a severe plastic deformation, thereby resulting in the appearance of the full austenitization and dynamic recrystallization (DRX) in the SZ. Therefore, the fine and equiaxed austenitic grains were produced on heating during FSSW, and then were transformed into fine martensite on cooling after FSSW. Similarly, the full martensite was also detected in the SZs of the FSSW DP600 and DP980 steels at the rotation rate of 3000 r/min[10,11]. However, the bainite was found in the SZ of the FSSW DP600 steel at the

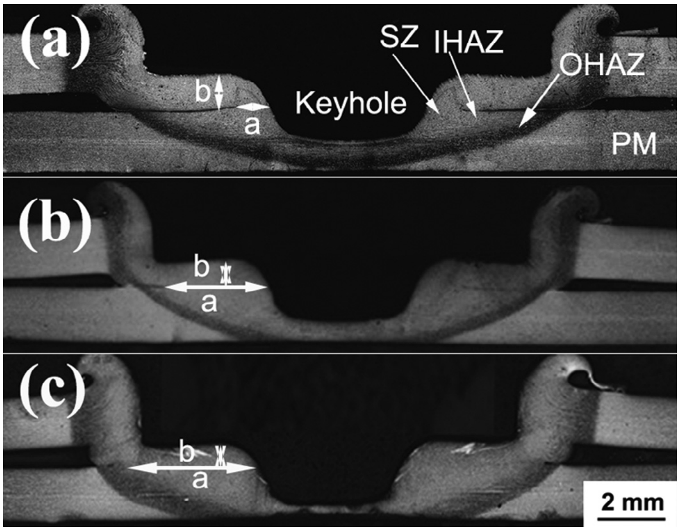

Fig. 2. Cross-section macrographs of FSSW DP780 at rotation rate of: (a) 500 r/min, (b) 1000 r/min, (c) 1500 r/min.