Resistance and friction stir spot welding of dual-phase (DP 780)—a comparative study

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Abstract

Among the AHSS, the dual-phase (DP) steels have been the subject of particular attention owing to their good combination of high strength and ductility and recent study focus on the weldability of these alloys. Resistance spot welding (RSW) is the primary sheet metal lap joining process in the manufacture of automotive assemblies. However, AHSS in RSW has revealed a number of problems that are a concern to the increased adoption of this range of alloys. Friction stir spot welding (FSSW) has been developed as an extension of friction stir welding (FSW). During FSSW, the rotating tool penetrates the sheets being weld and is then retracted producing a stir zone region that comprises a fine dynamically recrystallized microstructure. Solid-state metallurgical bonding was produced using a range of plunge rate, plunge depth, and tool rotational speed. The objective of this work is to compare the microstructure and mechanical properties on DP780 AHSS (1.6 mm thick) spot welds conducted using both process. The hardness, microstructure, failure mode, and bound area were examined. The results show that RSW has higher strength and bound area: the FSSW with decolorized advantage. Based on these results, we can provide the direction to choose the appropriate weld method.

Keywords Resistance spot welding · Friction stir spot welding · Advanced high strength steel · Dual phase 780 · Microstructure · Micro-hardness

1 Introduction

The use of advanced high-strength steels (AHSS), such as dual-phase and transformation-induced plasticity (TRIP) steels, has been steadily increasing over the past few years in automotive applications [1, 2–4]. This is due to the advantages that AHSS grades offer, in terms of higher strength that enables the automakers to decrease the vehicle weight for improved fuel economy and improved crash energy absorption for better occupant protection. The two grades of AHSS that

have seen increased use in automobiles steel grades that are used commercially in automotive bodies at present are those with minimum strength levels of 590 and 780 MPa. Resistance spot welding (RSW) is the predominant mode of fabrication in automotive production with a typical vehicle in North America containing about 4000 to 5000 welds. The mechanical and metallurgical changes in AHSS after the RSW operations are well documented in the literatures [2, 5]. The feasibility of automotive joining of AHSS using friction stir spot welding has been recently considered [5, 6]. Comparison of resistance spot welding and friction stir spot welding for DP 600 has also been reported [7], but the performance of DP 780 welded joints is still generally unknown.

There are two different types of fracture models that are generally observed in shear tension tests, namely button pull-out and interfacial fracture. In the interfacial fracture, the weld fails at the interface of the two sheets, leaving half of the weld nugget in one sheet and half in the other. In the button pullout, fracture occurs in the base metal or in the weld heat-affected zone at the perimeter of the weld. In this failure mode, the weld nugget is completely torn from one of the sheets with the weld remaining intact. The interfacial fracture, which is

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believed to have detrimental effects on the crashworthiness of the vehicles, is common occurrence when resistance spot welding dual phase steels [5, 8].

Friction stir spot welding (FSSW) is a relatively new discrete process derived from the continuous friction stir welding method developed at TWI, Abington, UK, in 1991 [9]. FSSW creates a spot, lap-weld without bulk melting. The majority of the research and development efforts on FSSW have been on aluminum alloys. Because Al alloys are easy to deform at relatively low temperatures (below about 550 °C), they are relatively easy to friction stir weld. Indeed, the development of FSSW for aluminum alloys has been quite successful. Mazda reported the first application of its 2003 RX-8 a mass production car. The entire Al rear door was friction stir spot welded [9–11]. To date, steel is the primary material for body structures of high volume mass produced car by all major car makers. Recently, friction stir spot welding for DP 600 dual phase steel can produce metallurgical bond, the bonding region in the thermo mechanical affect zone exhibited similar microstructure and hardness as in the base metal [6]. The friction stir welding begins with a rotating tool with spinning the tool and slowly plunging into the upper sheet of the lap joint. The heat generated by the rotating pin softens the material and facilitates the penetration of the pin. Then, the stirring phase enables the materials of two workpieces mix together to form the metallurgical bond around the rotating pin. Lastly, the forge pressure from the tool shoulder also keeps the interface between the two workpieces in intimate contact to facilitate the bonding. The tool is retracted at the end, leaving the characteristic hole in the middle of the weld. There is the different mechanism with RSW welds.

The resistance and friction stir spot welding processes are leading candidates for spot welding AHSS. The objective of this work was to compare the microstructural features of welds produced using these two processes. Metallurgical cross-sections and local hardness of various spot weld regions were examined. The fracture mechanisms in overlap tensile shear testing were studied and the relationship among peak failure load and bonded area was determined. The comparison of AHSS weld properties enables a benchmark for the evaluation of the weld performance of both the RSW and FSSW processes, which is important in weld process selection and welding procedure design.

2 Experimental procedure

2.1 Materials

DP 780 steels were galvanized with hot dipped coated 0.9 oz/ft² with hot-rolled to form the samples provided from Nippon Steel Corporation. The samples' size was supplied in a 1.6-mm sheet thickness. For testing, the steel sheets were sheared

into 40*125 mm coupons. The details of chemical composition were provided in the website which can search from the Nippon Steel Corporation of DP780.

2.2 Resistance spot welding

The RSW samples were fabricated using a pneumatically operated single phase RSW machine (Centerline Ltd., 300 kVA) with constant current and a frequency of 60 Hz. A truncated class 2 Cr-Cu alloy electrode with 6.0 mm face diameter was used as per AWS standards for 1.6-mm thick sheet. Cooling water flowrate and holding time also follow AWS recommendation of 4 L/min and 5 cycles respectively.

Resistance spot welding samples were produced over a range of force, current, and time parameters. The weld current was varied from 6 to 9 kA, the weld force ranged from 3.5 to 5.5 kN, and the weld time was between 10 and 20 cycles. The weld parameters optimized for tensile shear strength were 8 kA, 3.5 kN, 15 cycles and 8 kA, 3.5 kN, 20 cycles for DP 780. The weld samples were subjected to overlap tensile shear testing, micro-hardness testing and metallographic examination. A total of 4 tests were conducted per condition including three tensile tests, and one sample for metallographic preparation.

2.3 Friction stir spot welding

Friction stir spot welding was produced using a stir spot welder (MIRDC). Capabilities of this particular machine include tool rotation speed of up to 3000 rev/min and plunge rates (tool displacement rate) from 0.1 to 10 mm/s and dwell time from 2 to 10 s. The W-Re tool used for the spot welds had a truncated cone geometry, a pin diameter of 5 mm, a pin length of 2.5 mm, and a shoulder diameter of 10 mm.

Samples were produced for mechanical testing using a range of plunge rate, depth, and dwell time settings. The plunge rates were 0.1 and 0.5 mm/s while plunge depth varied from 1.8 to 2.6 mm. In all cases, the tool penetration depth was measured using a linear transducer with an accuracy of ± 0.07 mm.

2.4 Metallurgy and mechanical test

Joint mechanical properties were evaluated by measuring the peak load to failure during overlap tensile shear test according to JIS. The tensile shear test is according the JIS standard. The samples are prepared in 1.6 mm thickness, 40 mm in width, and 125 mm in length. The cross area is 40×40 mm². The tensile test samples are used tensile test machine (MIS8, USA) in the room temperature. The fracture surfaces of broken overlapped shear test specimens were examined using digital camera image. Finally, the cross-sectional area of the bonded region was measured by optical microscope image and

secondary electron image analysis. The samples of microscopy were prepared from grounded by silicon carbide paper with grit size from 200 to 2000 with 200 size increased in sequence. The samples were polished by 0.03 alumina and etched with 4% nital solution for 7–10 s at room temperature. Microstructures were observed and characterized by optical microscopy and scanning electron microscopy (JEOL 7100-F, Japan). The voltage was 20 Kv and working distance was 10 μm . The microhardness experiments have been verified more than 3 times. The values are too small to clearly point out the standard deviation. The distances of microhardness are measured from 0.1 mm per every point.

Micro-hardness testing of DP 780 steel sheet was carried out using a Shimadzu HMV-2 Vickers micro-hardness testing machine with a 300-g load and a holding time of 15 s. Microhardness testing revealed the hardness distribution and the individual hardness values in selected regions of welded joints.

3 Results and discussions

3.1 Resistance spot welding

To realize the microstructure change, the resistance spot welding was performed on the DP780 base metal. In the resistance spot welding, the electrodes clamp the workpieces with the pressure. At the same time, the current will be transduced into the workpieces. The current through the workpieces can form the resistance to produce heat in the faying face to form the weld nugget.

Based on the theory of RSW, the heat can influence the microstructure of alloy with weld process. The region of the weld nugget is classified into base metal (BM) (Fig. 1b), fine grain (FG) (Fig. 1c) in heat-affected zone (HAZ), coarse grain region (CG) (Fig. 1d), and fusion zone (FZ) (Fig. 1e) as can be clearly observed, as shown in Fig. 1. To validate the influences

Fig. 1 (a) A representative RSW weld cross-section shows microstructure for different weld sites labeled by b, c, d, e. (b) Region b (base metal). (c) HAZ region (c). (d) Coarse grain region (d) and (e) Fusion zone. Sample made with 8 kA, 3 kN and 20 cycles

of welding process within the thermal cycles, microhardness properties of examples were measured.

Figure 2 shows the hardness in the BM, FG, CG, and FZ regions. Hardness values in the BM range are from 280 to 310 Hv, which is an indication of the mainly ferrite of the microstructure (Fig. 2). In the Fig. 1b, the base metal of the DP 780 steel has a dual-phase microstructure consisting polygonal ferrite with colonies of martensite. Peak temperatures during welding in this region are typically below the martensite tempering temperature (i.e., $< 200\text{ }^{\circ}\text{C}$). Hardness values of FG are 280–400 HV; it indicated the volume fraction of martensite with a ferrite matrix increased (Fig. 1b). Within the FG, the peak temperature is well above A_{c3} , resulting in complete austenitization and grain growth. In the FG, the volume fraction of martensite increased. The peak temperature during welding in this region ranges from martensite tempering temperatures to just below the liquidus. Figure 1c shows a transitional region from the intercritical to the fine grained region within the HAZ, demonstrating that its microconstituents were considerably finer than those of either the base metal or the fusion zone. Peak temperatures in the intercritical region are between the A_{c1} and A_{c3} , resulting in a coarsening of the martensite phase. Within the fine grain region, temperatures exceed the A_{c3} resulting in complete austenitization. The austenite is inhomogeneous owing to the nature of segregation within the DP microstructure and short time above A_{c3} , resulting in the banding nature of martensite and the formation of fine grained ferrite. The hardness of CG region is about 440 HV. The image of microstructure shows that the volume of needle-like martensite is increased (Fig. 1d). From Fig. 2, it can be seen that hardness values are similar to those in the

HAZ region, ranging above 440 HV. The fusion zone shown in Fig. 1e consists of large needle-like martensite grains.

3.2 Friction stir spot welding

In Fig. 3a, the image indicated the overall view to demonstrate the different locations relative to the keyhole centerline in a FSSW spot weld in DP 780 sheet. The microstructures and hardness of base metal is similar to RSW case (Figs. 3b and 4). The microstructures of base metal showed martensite islands in a ferrite matrix (Fig. 3b). The intercritical region of the HAZ is significantly wider than the RSW case due to the longer welding times compared with RSW (Fig. 3c). The hardness value in HAZ region was 320 Hv (Fig. 4). Beyond the HAZ and towards the keyhole, the microstructure in the TMAZ region is comprised of a mixture of needle-like martensite and fine acicular ferrite, as shown in Fig. 3d. This region is subject to temperatures above A_{c3} and high strain rates, resulting in dynamic recrystallization and grain growth. The prior austenite grain size in this location was markedly increased. The hardness in the TMAZ was 360 Hv (Fig. 4). In addition to the needle-like martensitic microstructure, fine particles or rods of martensite are observed in Fig. 3d. Immediately beside the keyhole periphery, the stir zone microstructure is comprised of very fine grain martensite and porosity as shown in Fig. 3e. The grain size in the stir zone of friction stir spot welds is typically smaller than $10\text{ }\mu\text{m}$ in FSSW. The hardness in this particular location was 370 HV, as shown in Fig. 4.

3.3 Fracture mode analysis

The fracture mode was analyzed by tensile test according to JIS. The fracture mode has showed the pull-out surface with low failure load and interfacial fracture with high failure load occurred in the RSW cases (Fig. 5a, b). The FSSW cases showed that the pull-out fracture within the high and low failure load (Fig. 5c, d). The higher failure load accompanied with pull-out fracture mode seems that the RSW welding progress in the DP780 can be caused by current passed through the workpieces with complete melting and created the well connection between work joint (Fig. 5a). In the tensile test with the low failure load in the RSW workpieces showed the interfacial fracture, it seems be the inefficiency welding progress (Fig. 5b). The reason can be the current passed inefficiency, the clamp surface with the resistance, clamp stress difference and the no enough welding time. In the FSSW workpieces, the failure modes are all pull-out mode. The variants of FSSW weld can be the stress of pin, the welding time, the quality of pin, the rotation speed of pin, the friction of shoulder, the depth and surface area of pin and the base metal surface composition. In our experiments, the work joint in FSSW showed the pull-out fracture can be the pin contacted

Fig. 2 The Micro-hardness distribution of RSW cross-section in the top workpiece at 3/8 (1.0 mm) of the plate thickness, as measured from the top surface. The location of the BM, HAZ, coarse grain region and FZ are also illustrated in the figure

Fig. 3 (a) A representative FSSW weld cross-section shows microstructure for different weld sites denoted by b, c, d, e. (b) Region b (base metal). (c) HAZ region (c). (d) TMAZ region (d). (e) Stir zone (e). Sample produced tool rotation speed of 1800 rev/min, plunge rate of 0.2 mm/sec while the plunge depth of 1.9 mm and dwell time of 2 seconds

with the surface with the difference stress or the welding time not enough to form the different size welding nugget (Fig. 5c, d). In the resistance spot welding of galvanized steels, the expulsion of zinc (i.e., the element that melts and vaporizes first) is important to examine, as it limits the selection of the process parameters. Zinc can be expelled both at the electrode sheet interfaces, as shown in Fig. 5a, and at the interface between the two sheets where the weld forms [12–14].

In the friction stir spot welding of galvanized steels, zinc can be expelled at the tool sheet lower interface, as shown in Fig. 5c. Compared with FSSW, the typical surface appearance for RSW is considered more acceptable for automotive applications, the surface is smooth with a slight indentation and discoloration of the galvanized coating resulting from the thermal effects of the welding process.

The fracture surfaces produced in failed overlap shear testing specimens cause high and low fracture load values. The two types of fracture, interfacial and button-pullout, especially interfacial fracture, are often observed in spot welding. High and low fracture load shows interfacial fracture through the fusion zone of the resistance spot weld in Fig. 5a, b. A high fracture load means the model of fracture involved a partial pull out (Fig. 5c). During FSSW, the welded joint failed across the weld zone at the interface of the two sheets also called interfacial fracture, caused low fracture load (Fig. 5d). The fracture for RSW welds initiates at the interface and continues through the coarse grain region towards the centerline structure. This sequence indicates fracture occurring through a brittle mechanism. A similar brittle path is followed with FSSW welds where the crack initiates at the tip of the unbounded

Fig. 4 The Micro-hardness distribution of FSSW cross-section in the top workpiece at 3/4 (1.2 mm) of the plate thickness, as measured from the top surface. The location of the exit hole and the periphery of the tool shoulder are also illustrated in the figure

region and propagates through the stir zone under the shoulder. There was no change in failure mechanism observed in both process.

3.4 Bounded area and fracture load

Figure 6 shows the relationship between the failure load during overlap shear testing and the bonded area in completed welds. The failure load increased when the bonded area increased for both processes. Similar results have been reported during RSW and FSSW on DP 600 sheet materials [6].

Fig. 5 Weld and fracture surface for RSW and FSSW. (a) High fracture load RSW weld surface; (b) Low fracture load RSW weld surface; (c) High fracture load FSSW weld surface; (d) Low fracture load RSW weld surface

Fig. 6 Failure load vs. bonded area for the RSW and FSSW

4 Conclusions

In this study, mechanical and mechanical and metallurgical properties of RSW and FSSW DP 780 welds were compared. A correlation was found among failure loads, energy requirements, and bonded area for both processes. Also, partial tensile shear can be used to understand the initiation and propagation of cracks. From this it can be concluded that:

1. The microstructure of the HAZ is similar in both RSW and FSSW welds in DP 780. The intercritical and fusion regions consist of a mixture of martensite and ferrite, with increasing martensite volume fraction towards the weld centerline. The FSSW weld microstructure consisted of

a TMAZ between the HAZ and the stir zone. This region consists of a mixture of needle martensite, bainite, and ferrite. Martensite is observed in both the fusion zone and stir zone of the RSW and FSSW welds respectively. The morphology of the microstructure, however, is very different for both processes.

2. The microstructure hardness is similar in the FZ and stir zone for RSW and FSSW respectively. The hardness decreases from the weld centerline into the BM.
3. The failure load increased when the bonded area increased for both processes.
4. The fracture mode of tensile test of RSW showed 2 types included interfacial and pull-out fracture. The FSSW showed the pull-out fracture mode. It can indicate that the nugget can form with the different kinds of weld. The FSSW can form the complete nugget with size variation. The RSW to form the uncompleted nugget depends on the HAZ integration ability.
5. The failure load in RSW is higher than FSSW. In the future, to decide the weld option need to concern the strength and appearance of the application. The RSW can be used in the connected workpieces with high strength. The FSSW is the good choice for the decolorized with strength not the first priority.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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