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Metallurgical characteristics and failure mode transition for dissimilar resistance spot welds between ultra-fine grained and coarse-grained low carbon steel sheets

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ABSTRACT

We studied the microstructure and mechanical characteristics of spot welded specimens, fabricated from low carbon steel sheets with different microstructures. Both ultra-fine grained (UFG) steel sheet and coarse grained (CG) steel sheet were used. The refined microstructure of the UFG steel has been produced by severe plastic deformation (SPD) using the constrained groove pressing (CGP) method. The grain size of the base metals was approximately 260 nm and 30 μm in diameter, respectively, in the UFG and CG steels. Examining the microstructure of a cross section cut through the spot weld reveals a similar grain size and phase distribution in the nugget on both the sides of the initial interface between sheets. Some recrystallization is observed in the heat affected zone on the UFG side as previously reported after the welding of symmetrical UFG–UFG spot welded specimens. The same energy deposit produces larger nuggets after the spot welding of UFG steels. Moreover, the hardness distribution across the nugget changes after welding on both sides of the initial (UFG/CG) interface. This effect is presently attributed to a change in the solidification, cooling rate and tempering after welding, likely because the higher resistance of UFG steel sheets increases the heat release by the Joule effect during spot welding. These changes in the mechanical behavior modify the transition between the interfacial failure (IF) and pull out failure (PF) mode with respect to energy deposit.

1. Introduction

Ultra-fine grained (UFG) metals have unique mechanical properties that have recently attracted attention for industrial applications. Severe plastic deformation (SPD) can efficiently produce UFGed materials. Among the processes leading to intense cold working [1–3], the constrained groove pressing (CGP) method has been demonstrated to be able to improve the strength and hardness of metal sheets [4–6]. In particular, we have reported that the CGP method can be applied to steel sheets [7,8]. The low carbon UFGed steel sheets that are produced in that way provide an excellent strength to weight ratio that could be especially valuable for the automotive industry. We have also found that an appropriate post-annealing of UFGed metals produced by SPD considerably improved the ductility with only a slight strength loss [9]. Joining dissimilar UFGed and CGed metals is essential for practical applications because the UFGed materials can presently only be produced in small sizes. Resistance spot welding is the most common technology used in the automotive industry, and it has the highest throughput [10,11]. The spot welding of high strength steels produces peculiar gradients of microstructures across the weld because it induces phase changes, recrystallization and tempering of the base metal in the fusion zone (FZ) of the weld nugget, and in the heat affected zone (HAZ) [12]. We have especially observed that spot welding affects the mechanical properties of low carbon UFGed steels [13–15]. Some previous papers have reported on spot welded structures made of different high strength steels including DP780-DP600 [16], DP600-low carbon steel [17], BH180-AISI304L or BH180/IF7123 steels [18], and low carbon-austenitic stainless steel [19,20]. The present paper sheds some light on the metallurgical evolution and mechanical behavior of practical spot welded structures containing both UFGed and CGed steel sheets. A relatively large range of welding conditions is presently explored. Changes in microstructures are examined by optical microscopy (OM) and transmission electron microscopy (TEM). The mechanical behavior of the welded samples is examined using tensile-shear tests.

2. Experimental procedure

2.1. Materials and processing

The starting material used in this work was low carbon steel sheets with a thickness of 3 mm and a chemical composition of

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Fe–0.053C–0.023Si–0.203Mn–0.009Cr–0.028Ni–0.003Mo–0.006P–0.003S in the as-received condition. These coarse-grained low carbon steel sheets were subjected to the constrained groove pressing process for up to two passes to impose an equivalent plastic strain of 2.32 to produce the ultra-fine grained structure. The details of the CGP method as a SPD process of sheet forming metals are described in the previous literature[4,8,21]. However, a short description of this technique is provided here. A set of asymmetrical grooved dies and a set of flat dies with a gap distance equivalent to the sheet thickness are utilized in constrained groove pressing. Each pass of the CGP process includes two corrugation and two flattening states. In the corrugation stages, the inclined regions of the pressed sample are subjected to pure shear deformation under the plain strain condition, and no deformation is induced in the flat regions. After each corrugation stage, the grooved sample is placed between the flat dies and straightened. In each corrugation or straightening stage, an equivalent plastic strain of ~0.58 is imparted on the deformed regions but in the opposite directions. A sample rotation by 180° around the *Y*-axis, which is perpendicular to the sheet plane, is required after alternating one corrugation and one flattening step. This process ensures that the un-deformed regions are deformed during the second groove pressing and flattening due to the asymmetry of the grooved dies. Thus, the alternating pressings with grooved dies and flat dies result in a homogenous strain distribution throughout the sample without any changes in its dimensions. Generally, two groove pressing and two flattening stages compose one CGP pass and impose an equivalent strain of ~1.16 to the deformed sheet. Finally, a relatively uniform UFGed structure can be obtained after a multi-pass CGP process.

In the next step, the mentioned coarse-grained as-received and ultra-fine grained low carbon steel sheets were resistance spot welded similarly and dissimilarly to each other at with different welding parameters. The utilized dissimilar design was as schematically demonstrated in Fig. 1. Resistance spot welding joins two or more metal sheets by heat generation at the sheet interface resulting from the Joule effect [22], owing to applied current, welding cycle, force exerted by the electrodes and the increase of the metal resistance to current flow. In this work, electrode force was kept at a fixed value of 4 kN and the effects of the welding current in the range of 8.2–17.3 kA at constant numbers of welding cycles of 12, 16 and 20 were examined. A 120 kVA pneumatic resistance spot welding machine equipped with water cooled copper–beryllium conic-shaped electrodes with a face diameter of 6.5 mm were utilized in all experiments.

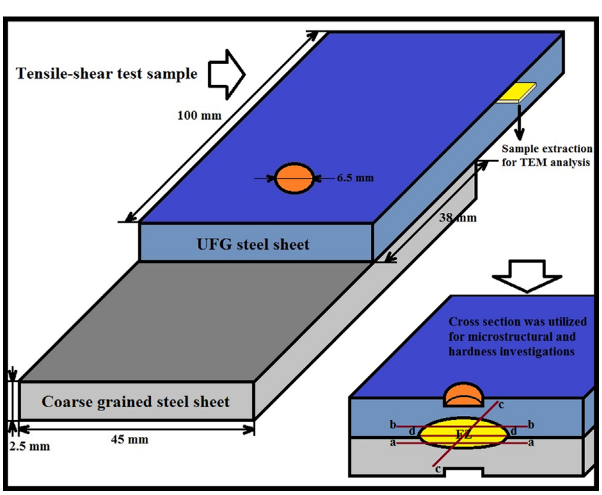

Fig. 1. Joint design and sample preparation approaches for different microstructural and mechanical investigations.

2.2. Characterization

2.2.1. Initial and constrained groove pressed low carbon steel sheets

2.2.1.1. Mechanical behavior. Tensile and macro-hardness tests were performed to monitor the evolutions in mechanical properties of coarse-grained (CG) as-received low carbon steel sheet and ultra-fine grained (UFG) low carbon steel sheet fabricated by CGP process. Tensile samples were machined according to ASTM E8/E8M-11 [23] with a gage length of 32 mm. Afterward, experimental test was carried out at initial strain rate of $5\times10^{-4}\,s^{-1}$ utilizing an Instron Universal Tensile Loading Machine. Hardness profiles across the middle of thickness cross section and along the length of CGed and UFGed samples were evaluated using a Vickers macro-hardness instrument (Bohler, Germany) and employing 30 kg applied load for 20 s dwell time in each measurement taken at 8 mm distance intervals.

2.2.1.2. Microstructural features and physical properties. The microstructures of as-received and constrained groove pressed low carbon steel sheets were examined using optical microscopy. Sample preparation for these studies was performed across thickness section using electron discharge machining (EDM). Thereafter, the standard metallographic procedure was carried out employing grinding papers of different numbers (320, 600, 800, 1000, 1500, 2000, and 3000) and diamond pastes down to an average size of 1 μm. The microstructural details were revealed using a chemical solution containing 96% C_2H_5OH and 4% HNO_3. Subsequently, optical microscopy observations were performed under an Olympus digital camera equipped with Clemex image analyzer software (Olympus PME3 equipped with a digital camera and a CLEMEX-BX51M image analyzer, Germany). Moreover, microstructural investigations across thickness sections of similar and dissimilar resistance spot welded samples were performed with the same procedure as schematically demonstrated in Fig. 1. Stereographic macro-imaging was utilized to observe the macrostructures and cross sectional profiles of spot welded samples at low (14.4 kA, 16 cycles) and high heat inputs (15.9 kA, 20 cycles) by using stereo microscope (Nikon, USA). Low heat input spot welded samples are in fact samples welded with the minimum current density to get pull out failure. This case is usually referred as optimal conditions for spot welding. But, the high heat input parameter was considered to examine the effects of liquid metal ejection outside the weld nugget on the microstructural characteristics and mechanical performance of spot welds. With the mentioned procedure, microstructural features across thickness section of these low and high heat inputs joined spot welds were studied in detail at different zones including base metal (BM), heat affected zone (HAZ), and fusion zone (FZ). Ultra-fine grained structure of CGPed low carbon steel sample was revealed by utilizing transmission electron microscopy (TEM, JEOL 2000FX, Japan) analysis. Sample for TEM studies was prepared according to the following three stages; at first EDM cutting as shown in Fig. 1, schematically, secondly, consecutive mechanical thinning (grinding and polishing) to thickness ~50 μm, and finally ion polishing to create the holes (Ion milling, JEOL, Japan). Developments in the physical properties of low carbon steel sheets before and after fabrication of ultra-fine grained structure were assessed in terms of electrical resistivity. The resistivities of coarse-grained as-received and ultra-fine grained steel sheets were measured by the four-point probe technique because resistivity controls heating during spot welding. In this approach, the four metal tips as a part of an auto-mechanical stage travels up and down during measurements. Samples' resistivity was determined by utilizing a high impedance current source, a voltmeter, and 4-probes with 4 mm spacing.