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Resistance spot welding of MS1200 martensitic advanced high strength steel: Microstructure-properties relationship

M. Pouranvari*, S. Sobhani, F. Goodarzi

Department of Materials Science and Engineering, Sharif University of Technology, Tehran, Iran

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ABSTRACT

This paper addresses the microstructure and tensile-shear mechanical performance of MS1200 Giga-grade martensitic advanced high strength steel resistance spot welds. The key phase transformations in MS1200 welds were lath martensite formation in the fusion zone (FZ) and upper-critical heat affected zone (HAZ), new ferrite formation in the inter-critical HAZ and martensite tempering in the sub-critical HAZ. The MS1200 welds were featured by a near matching hardness in the fusion zone and under-matching hardness in the heat affected zone (HAZ) compared to the base metal. At certain process window a complete nugget pullout and separation was observed with high post-necking tearing energy. The interfacial to pullout failure mode transition was explained in the light of FZ hardness as well as the HAZ softening associated with martensite tempering in the sub-critical HAZ. The load bearing capacity of MS1200 welds failed at interfacial mode was strongly depends on the FZ size as well as the FZ hardness. However, the peak load of welds failed at pullout mode was a function of HAZ softening as well as the plastic constraint in the HAZ associated with the hard upper-critical HAZ/FZ and martensitic BM.

1. Introduction

Advanced high strength steels are key materials for lightweight design strategies in automotive industry to achieve energy conservation, improvement of safety, and crashworthiness qualities [1,2]. The structural reinforcement components in vehicle's safety cage composed of pillars, side sills, rockers, door reinforcement beams, roof rails and floor and roof cross members require Giga-grade steels with tensile strength more than 1 GPa. Therefore, extremely high strength steels, typically martensitic steels and press hardening grades, are one of the best promising candidates for the use in these components [3,4].

Resistance spot welding (RSW), which is the key joining process in automotive industry, plays critical role in vehicle manufacturing [5]. Body-in-white of the automotives contains several thousands spot welded joints depending on the size of the vehicle and the number of parts that need to be joined in combination and the joining strategy of the manufacturer [6]. Therefore, the mechanical performance of the RSWs plays key role in crashworthiness of the vehicle, the capability of a car structure to provide adequate protection to its passengers against injuries in the event of a crash [7]. Moreover, the failure of spot welds may affect the vehicle's stiffness and NVH (Noise, Vibration and Harshness) performance on a global level [8]. Therefore, the quality, performance and the failure characteristics of resistance spot welds (RSWs) are important for determination of durability and safety design of the vehicles. Hence, a fundamental knowledge of the failure process of the resistance spot welds is required to achieve sound, strong and reliable welds. Failure mode of resistance spot welds (RSWs) is a qualitative measure of mechanical properties [1–16]. The avoidance of interfacial failure (i.e. fracture through the fusion zone) is one of the key requirement for resistance spot welds in safety critical areas of the vehicle [5,6]. Generally, the pullout failure mode in which the failure occurs via withdrawal of the weld nugget from one sheet exhibits the most satisfactory mechanical properties. The pullout failure mode during quality control indeed indicates that the same weld would have been able to transmit a high level of force, thus cause severe plastic deformation in its adjacent components, and increased strain energy dissipation in crash conditions [17]. Therefore, it is needed to adjust welding parameters so that the pullout failure mode is guaranteed.

Past researches have shown that the resistance spot welds made on AHSS steels display high susceptibility to fail in interfacial mode [5,10,13,17]. Complexity of failure process in AHSS spot welds is originated from complex weld phase transformation including maretnite formation in the fusion zone (FZ) and softening in the heat affected zone (HAZ) [1–20] and segregation phenomena [21,22]. It is shown that the IF to PF failure mode transition is largely depend on the complex interplay between weld geometry, fusion zone/HAZ/base metal properties, test geometry,

* Corresponding author.
E-mail address: pouranvari@sharif.edu (M. Pouranvari).

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Table 1
Chemical composition and mechanical properties of investigated MS1200 steel.

Chemical composition (%wt.)					Mechanical property		
C	Mn	Si	Cr	Ni	YS (MPa)	UTS (MPa)	El (%)
0.09	1.5	0.18	0.04	0.04	1240	1330	5

YS: Yield Strength, UTS: Tensile Strength, El: Elongation.

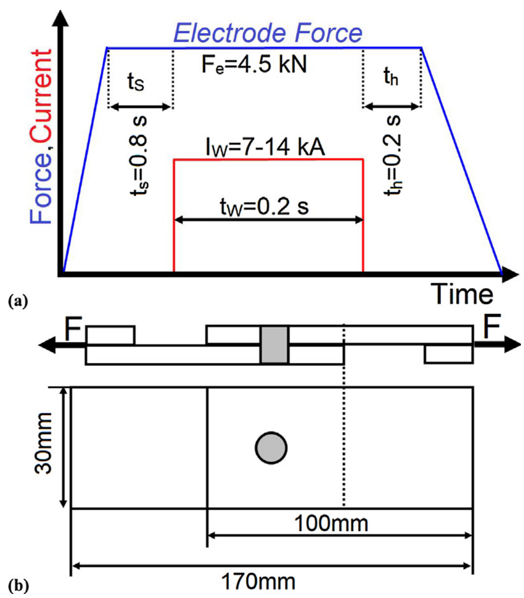

Fig. 1. (a) Schedule of resistance spot welding used in this study for joining MS1200 martensitic steel sheets, (b) schematic of tensile-shear samples.

and the stress state in each weld [1–25]. Therefore, a fundamental knowledge of microstructural evolutions during welding of AHSS automotive steels is vital to produce sound, strong and reliable joints and to predict the failure behavior of welded joint.

Compared to other AHSS types, the welding behavior of martensitic grades are less investigated [26–29] and therefore further clarifications on structure-properties relationships in martensitic AHSS steel resistance spot welding are required. This paper aims at understanding the microstructure and mechanical properties of the MS1200 martensitic advanced high strength steel during resistance spot welding.

2. Experimental methods

This study concerned the joining of uncoated cold rolled MS1200 martensitic AHSS (Docol 1200 M) sheet using resistance spot welding. Table 1 shows the chemical composition and the tensile properties of the steel. The sheet thickness was 1.5 mm.

Resistance spot welding was performed using a 120 kVA AC pedestal type resistance spot welding machine operating at 50 Hz controlled by a programmable logic controller (PLC). Welding was conducted using a 45-deg truncated cone RWMA (resistance welding manufacturing alliance) class 2 electrode with 8-mm face diameter. Fig. 1a shows the welding schedule. In this work, the effect of welding current, as the main variable of RSW, was studied on the microstructure/properties of the welds. Therefore, welding current was incrementally increased from 7 to 14 kA with a step size of 1 kA. Three samples

Mechanical performance of the welds was evaluated using quasi-static tensile-shear testing. The dimensions for the tensile-shear test are illustrated in Fig. 1b.[1] The tensile-shear tests were performed at a cross head of 10 mm/min. Failure modes were determined by observing the weld fracture surfaces. Mechanical performance of the welds is described in terms of peak load (P_{max}) and failure energy (W_{max}). The W_{max} was digitally calculated by measuring the area under the load-displacement curve up to the peak point. The data points for peak load and failure energy are average of two specimens.

Optical microscopy and scanning electron microscopy (SEM) was used to examine the structure of the spot welds at both macro and micro scales. Samples for metallographic examination were prepared using standard metallography procedure and were etched using Nital solution. Vickers micro-hardness test was performed using an indenter load of 100 g for a period of 20 s to obtain hardness values in different zones of the weldment. To increase the accuracy in reading of the indentations sizes, they were measured using image analyzer software (ImageJ) under optical microscopy.

3. Results and discussion

3.1. Tensile-shear properties

Results showed that the welding current has a profound effect on the load-displacement characteristics of MS1200 resistance spot welds (Fig. 2a). Three distinct types of load-displacement curves were observed as a function of welding current. To describe the mechanical performance of the welds two parameters were extracted from the load-displacement curves: peak load (i.e. the peak point at load-displacement curve) and failure energy (i.e. the area under load-displacement curve up to the peak point). The peak load (P_{max}) represents the maximum force sustainable by the spot welds before failure initiation and the failure energy (W_{max}) represents the energy absorption capability of the welds before failure initiation. Fig. 2b shows the effect of welding current on the P_{max} and W_{max} indicating that increasing welding current up to 11 kA enhances both load bearing capacity and energy absorption capability. However, increasing welding current beyond 11 kA does not improve the mechanical properties of the welds. According to AWS D8.7:2005 [30], the minimum acceptable peak load for 1.5 mm MS1200 spot welds is 24.9 kN. Therefore, according to Fig. 2b, the minimum acceptable welding current is 10 kA.

Four failure modes were observed during the tensile-shear loading of the MS1200 weld, as illustrated in Fig. 3. The failure mode was a function of welding current. Effect of welding current on failure mode is indicated in Fig. 2b. Welds made using current lower than 10 kA were failed in full interfacial failure (IF) mode. Joints made using welding current of 10 kA was failed at partial interfacial accompanied with partial thickness-partial pullout (PT-PP). Based on the first failure path, this failure mode was categorized an interfacial fracture. Increasing welding current to 11 kA changes the failure mode from IF to complete double side nugget pullout and separation. However, upon increasing welding current to 13 kA and more, where welding is accompanied with severe expulsion, the failure mode was changed to PT-PP. Each failure mode exhibits a characteristics load-displacement curve (Fig. 2a). The failure mode affects the shape of tail in load-displacement curves. In IF mode, the load suddenly dropped to zero due to the rapid progression of the failure process. In complete nugget pullout and separation mode, the peak point corresponds to the necking of the nugget

[1] It should be noted that the width of test sample in this study (i.e. 30 mm) is less than that of recommended by AWS D8.7 standard (i.e. 60 mm) [31]. The narrow specimens used in this study provide lower restraint to the weld, and therefore, a weld failing in pull-out mode in such specimens may fail in interfacial mode if the specimens are wider [8].