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Fracture toughness of martensitic stainless steel resistance spot welds

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ABSTRACT

The paper is focused on the strength and fracture toughness of AISI420 martensitic stainless steel resistance spot welds under the tensile-shear loading. The failure behavior of AISI420 spot welds was featured by quasi-cleavage interfacial failure with low load bearing capacity and weak energy absorption capability which was a function of the weld fusion microstructure, predominately carbon and chromium rich martensite plus δ-ferrite. Fracture toughness of the fusion zone proved to be the most important factor controlling the peak load of the spot welds made on AISI420 failed in interfacial mode. A geometry-independent fracture toughness of the weld nugget (c.a. 23 $MPam^{0.5}$) was determined using fracture mechanics concept. Through modeling it was found that there is a critical fracture toughness which beyond that the pullout failure mode can be obtained which is a function of sheet thickness and tensile strength of the base metal.

1. Introduction

Spot weld failure during a crash is a critical issue for crashworthiness, stiffness and NVH (Noise, Vibration and Harshness) performance of the vehicle. Therefore, a fundamental knowledge of the failure process of the spot welds are required to achieve sound, strong and reliable welds [1]. Analyzing and predicting the spot welds performance and their failure is a challenging problem due to complexity of the spot welds originating from several aspects including following ones:

(i) Heterogeneous metallurgical structure: Due to thermal cycle of the welding process the original microstructure of the base metal is destroyed producing a steep gradient in microstructure and mechanical properties across the weldment. Phase transformations in the fusion zone and heat affected zone affects the hardness, strength and toughness of the materials which can deteriorate the mechanical properties of the weld [2–9].
(ii) The unique and complicated geometrical features: A resistance spot weld can be considered as an axisymmetrically notched body [10] (i.e. creating a spot weld produces a notch around itself). The behavior of the notch under loading is a critical issue in determining the failure behavior of the weldment. Other factors such a electrode indentation and shrinkage voids and porosity can also act as stress concentration sites [1].

Therefore, the failure mode and failure mechanism of the spot welds largely depend on the complex interplay between weld geometry, materials properties of base metal (BM), fusion zone (FZ) and heat affected zone (HAZ), test geometry, and the stress state in the weld [1,11–14]. Generally, spot welds can fail in two distinct modes [1]: (i) Interfacial failure (IF) mode in which, the fracture propagates through the fusion zone. It is believed that this failure mode has detrimental effect on the crashworthiness of the vehicles and (ii) Pullout failure (PF) mode in which, the failure occurs via withdrawal of the weld nugget from one sheet. Generally, the PF mode exhibits the most satisfactory mechanical properties.

Materials selection is a critical issue in vehicle design. The driving force for materials evolutions in motor vehicles and railed vehicles are light-weighting, energy conservation, environmental protection and improved crashworthiness [1]. Besides a great deal of much attention on advanced high strength steels, stainless steels with superior corrosion resistance, unique work-hardening behavior and excellent energy absorption capability are promising materials for transportation applications [15–18]. Therefore, high strength martensitic stainless steels are good candidates for high-stiffness, load-transferring barriers and anti-intrusion barriers (e.g. side frame, crash box, door reinforcement, bumper beam and front subframe) to crash managing and protection of passenger during impact collisions [19].

Martensitic stainless steels exhibit a good strength-formability combination in annealed conditions and then they can achieve higher strength via hot stamping process [20]. MSS have been considered as potential complementary solutions to existing press hardening steels. In contrast to martensitic boron carbon steels, high corrosion/oxidation resistance of MSS eliminate the need for expensive coatings for oxidation protection during hot-stamping process which make them

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compatible with fast heating processes. Moreover, due to their high hardenability, very slow cooling rate (ca. 1 Ks^{-1}) is sufficient to achieve martensitic microstructure [21–23]. The conventional joining process involves resistance spot welding after hot stamping process. In this process the HAZ softening due to martensite tempering limits the achievable joint strength. Recently, an emerging technology so-called hot stamping spot welding tailored blank technology is under development in which the annealed soft blank is resistance spot welded before performing hot stamping process [24,25]. This process eliminates the occurrence of the HAZ softening and the subsequent quenching during hot stamping produces relatively uniform hardness distribution across the weldment [24,25]. The key requirement in this process is the avoidance of weld failure during hot stamping process. It is also a vital issue for hot stamping of patchwork blanks, where the local stiffness and mechanical performance is enhanced by spot welding a reinforcing patch to the main forming blank [26,27]. Therefore, the metallurgical behavior of annealed martensitic stainless steels with initial ferritic microstructure during resistance spot welding and their failure characteristics is important for their implementation in the automotive body-in-white.

The aim of this work is to investigate the failure characteristic of annealed AISI420 martensitic stainless steels spot welds under tensile-shear loading. It was examined that which material properties played dominant role in controlling the strength of the martensitic stainless steel spot welds. It was found that the tensile-shear strength of the welds is governed by the fracture toughness of the fusion zone. Then, the fracture toughness of the fusion zone is determined and its validity is discussed.

2. Materials and method

This study concerned the joining of AISI420 martensitic stainless steel (MSS) using resistance spot welding. The sheet thickness was 1.5 mm. The chemical composition and mechanical properties of the investigated steel are given in Table 1.

Despite the fact that the surface of the sheets was almost free from grease and dirt, to ensure consistent cleanliness of the sheet steels, they were cleaned with cotton prior to the welding experiments. Resistance spot welding was performed using a PLC controlled, 120 kVA AC pedestal type resistance spot welding machine. Welding was conducted using a 45° truncated cone RWMA Class 2 electrode with 8-mm face diameter. Fig. 1a shows the welding schedule.

The quasi-static tensile-shear test samples were prepared according to ANSI/AWS/SAE/D8.9-97 standard [28] (Fig. 1b). The tensile-shear tests were performed at a crosshead speed of 10 mm/min. Peak load (measured as the peak point in the load-displacement curve) and failure energy (measured as the area under the load-displacement curve up to the peak load) were extracted from the load-displacement curve. Failure modes of spot welds were determined by observing the weld fracture surfaces.

Samples for metallographic examination were prepared using standard metallography procedure. The metallographic samples were etched by Villela reagent (1 gr picric acid, 5 ml HCl, 100 ml ethanol). Weld microstructures and macrostructures were examined under optical microscopy. Vickers microhardness test, was used to assess the hardness values of the weldment. An applied load of 100 g and a time of 15 s were used. To increase the accuracy in reading of the indentations sizes, they were measured using an image analyzer software (ImageJ) under optical microscopy.

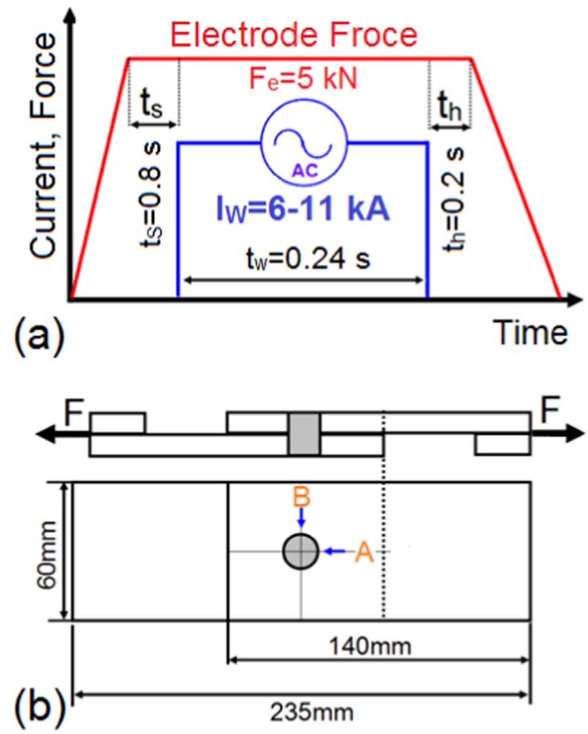

Fig. 1. (a) Welding Schedule, t_S: squeeze time, t_W: welding time, t_h: holding time and I_W: welding current (b) the tensile-shear specimen dimensions. Point A experiences maximum stress intensity factors K_I and K_{II}. Point B experiences the maximum stress intensity factor K_{III}.

3. Results and discussion

3.1. Metallurgical and physical weld attributes

Fig. 2a shows a typical macrostructure of AISI420 stainless steel resistance spot welds indicating a heterogeneous structure including three distinct microstructural zones: FZ, HAZ and BM. The hardness profile across the weldment (Fig. 2b) confirms the presence of microstructure gradient in the weldment (Fig. 3a):

(i) Base metal (BM): Fig. 3b shows the microstructure of the BM indicating a ferrite matrix decorated with carbides particle which are essentially Cr-rich carbides. The average hardness of the BM is 220 HV which is in accordance to its microstructure.

(ii) Fusion zone (FZ): Fig. 3c shows the FZ microstructure exhibiting a completely different microstructure. The FZ consisted of martensite with some amount of δ-ferrite along solidification grain and sub-grain boundaries. It is of note that there is a narrow region of equiaxed dendritic zone at the weld nugget edge (Fig. 3d). This zone was formed by a mechanism similar to that of the formation of the equiaxed chill zone in cast ingots [29]. However, the microstructure of all regions in the FZ is nearly the same (i.e. dual phase microstructure of martensite and δ-ferrite). The phase transformation sequence in the FZ can be explained with the help of to pseudo-binary equilibrium Fe-

Table 1
Chemical composition and mechanical properties of the investigated AISI 420 martensitic stainless steel.

Chemical composition, wt%								Mechanical properties		
C	Mn	Si	Cr	Ni	Cu	V	Fe	YS, MPa	UTS, MPa	TEL, %
0.34	0.55	0.30	12.9	0.09	0.03	0.06	Base	377	566	60

*YS is yield strength; UTS is ultimate tensile strength; TEL is total elongation.