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PREDICTION OF FAILURE MODE IN AISI 304 RESISTANCE SPOT WELDS

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Abstract

Failure mode is a qualitative measure of resistance spot weld (RSW) performance. To ensure reliability of resistance spot welds during vehicle lifetime, process parameters should be adjusted so that the pullout failure mode is guaranteed. In this paper, failure mode of AISI304 resistance spot welds is studied under quasi-static tensile-shear test. Results showed that the conventional weld size recommendation of $4t^{0.5}$ is not sufficient to guarantee pullout failure mode for AISI304 steel RSWs during tensile-shear test. It is required to search for new weld quality criterion for resistance spot welded austenitic stainless steels. Considering the failure location and failure mechanism in the tensile-shear test, minimum required fusion zone size to ensure the pullout failure mode was estimated using an analytical model. According to this model, in addition to sheet thickness, ratio of fusion zone hardness to failure location hardness is the key metallurgical factor governing failure mode of spot welds during the tensile-shear test.

Key words: resistance spot weld; failure mode; fusion zone size; austenitic stainless steel

Introduction

Resistance spot welding is widely used to join sheet metals in the automotive industry. The quality and performance of the spot welds significantly affect the durability and safety design of the vehicles [1]. Spot weld failure mode is a qualitative measure of the weld quality. Generally, the resistance spot weld (RSW) failure occurs in two modes: interfacial and pullout. In the interfacial mode, failure occurs via crack propagation through fusion zone, while in the pullout one, failure occurs via complete (or partial) nugget withdrawal from one sheet. Spot welds that fail in the nugget pullout mode provide higher peak loads and energy absorption levels than spot welds that fail in

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the interfacial fracture one. To ensure reliability of spot welds during vehicle lifetime, process parameters should be adjusted so that the pullout failure mode is guaranteed [2-4].

Fusion zone (FZ) size and its microstructure is the most important parameter determining its mechanical behavior. Various industrial standards have recommended a minimum weld size for a given sheet thickness. For example, American Welding Society, American National Standards Institute, and Society of Automotive Engineers (AWS/ANSI/SAE) [5] have recommended equation (1).

$$d = 4\sqrt{t} \tag{1}$$

where: d is diameter of fusion zone, mm and t is thickness of plate, mm.

Nowadays, application of stainless steel in car body is under review. Most of the present guidelines and recommendations are for low carbon steel and there is limited information concerning spot weldability of stainless steels. Therefore, investigating resistance spot weld behavior of these materials is of utmost importance.

The objective of the research is to detail the failure mode of austenitic stainless steel AISI 304 spot welds. Critical fusion zone size to ensure nugget pullout mode during the static tensile-shear test is predicted using an analytical model.

Experimental Procedure

An austenitic stainless steel (SS) sheet 1.2 mm thick was used as the base metal. The chemical composition of the base metal was Fe-18.47 Cr-9Ni-1 Mn-0.462 Cu-0.016 Nb-0.388 Si-0.035C-0.038P-0.004S corresponding to AISI 304 stainless steel. Spot welding was performed using a PLC controlled 120 kVA AC pedestal type resistance spot welding machine. Welding was conducted using a 45-deg truncated cone RWMA Class 2 electrode with 7-mm face diameter. Welding current was varied from 5 kA to 10.5 kA and welding time, electrode pressure and holding time were fixed at 12 cycles, 4 bar and 30 cycles, respectively.

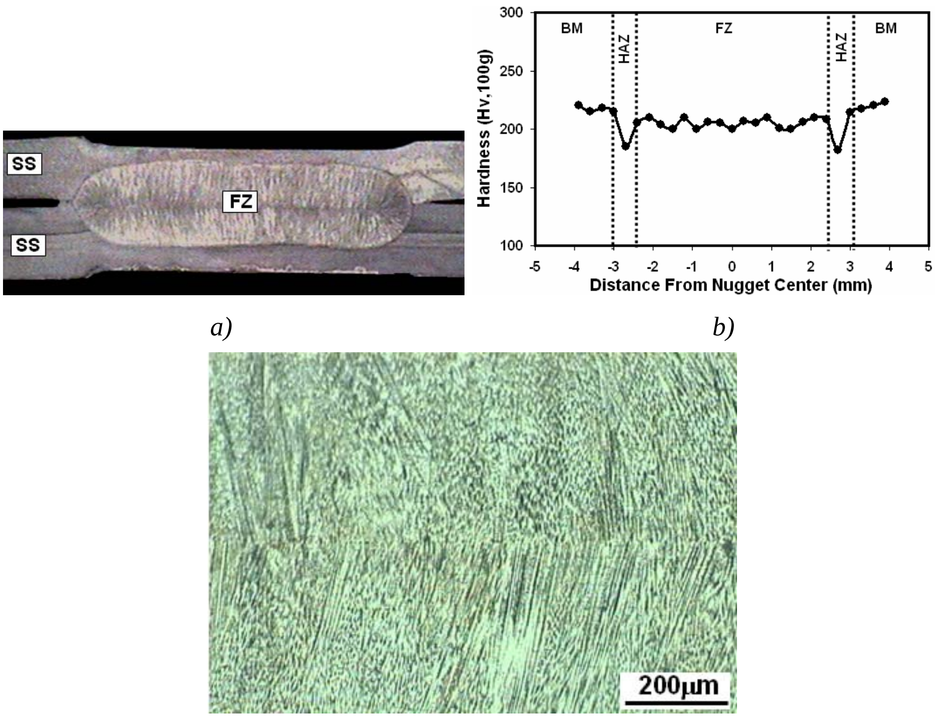
The static tensile-shear test samples were prepared according to ANSI/AWS/SAE/D8.9-97 standard [5]. The tensile-shear tests were performed at a cross head of 2 mm/min with an Instron universal testing machine The Failure mode was determined from the failed samples. Samples for metallographic examination were prepared using standard metallography procedures. Optical microscopy was used to examine the microstructures and to measure physical weld attributes. After complete separation in the tensile-shear test, failure surface was examined using an stereo optical microscope.

Microhardness test was used to determine the hardness profile of the joints, using a 100g load on a Shimadzu microhardness tester. The microhardness traverses were performed on a diagonal covering microstructural zones in both sheets. The indentations were spaced 0.3 mm apart.

Results and discussion

Microstructure and hardness profile

Hardness characteristic of the resistance spot welds is one of the most important factors affecting their failure behavior**.** Fig. 1(a, b) shows a typical macrostructure and hardness profile of the SS spot weld joint. As can be seen, there is a small variation across the joint. Since austenitic stainless steel base metal is not transformable, no hardening was occurred in the FZ. The microstructure of the FZ is austenitic, as shown in Fig. 1c. The hardness of the FZ is somewhat lower than the BM which can be attributed to its cast microstructure and the presence of coarse columnar grains. Moreover, the effect of the prior work hardening, if any, is completely removed in the FZ because of the melting. Observable softening was found in the HAZ adjacent to the FZ, where the local hardness of 175 HV was lower than the BM hardness of 210 HV. Slight reduction in the hardness of HAZ can be attributed to the grain growth and the lost of possible prior work hardening. The hardness profile observed for SS weld is in contrast to that reported for low carbon steel, in which the FZ hardness is significantly higher than the BM [6-7]. This difference is also attributed to absence of austenite decomposition.



c)

Fig. 1 A typical a) macrostructure b) hardness profile and c) the FZ microstructure of stainless steel spot weld.

Critical FZ size

Two distinct failure modes were observed during the static tensile-shear test: interfacial fracture and nugget pullout (as shown in Fig. 2). Experimental results showed that increasing welding current alters the failure mode from the interfacial failure to the pullout failure.

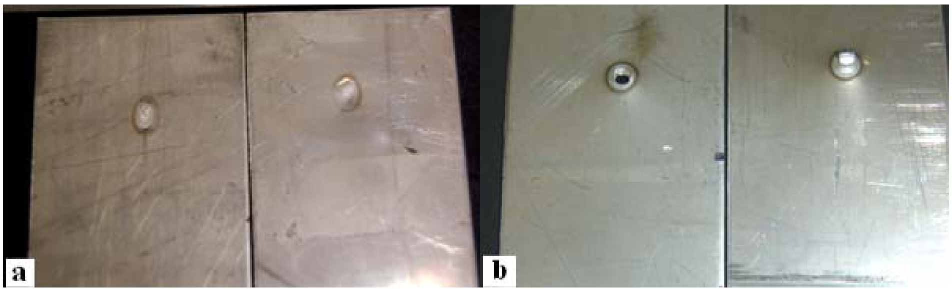


Fig. 2 Observed spot weld failure modes: a) interfacial, b) nugget pullout

Failure of the spot welds can be considered as a competitive process, i.e. failure occurs in a mode which needs less force. During tensile-shear test, the shear stress at the sheet/sheet interface is the driving force for the interfacial mode, and the tensile stress at the nugget circumference is the driving force for the pullout failure mode [8-9]. Each driving force has a critical value and the failure occurs in a mode which its driving force reaches its critical value, sooner. The FZ size is the governing parameter determining stress distribution. For small weld nuggets, the shear stress reaches its critical value before the tensile stress causes necking; thus, failure tends to occur under interfacial mode. Therefore, there is a critical weld FZ size beyond which, the pullout failure mode is expected.

Fig. 3 shows peak load versus FZ size for the SS/SS combinations. The minimum FZ size required to ensure pullout failure mode is determined. SS/SS welds exhibit a pullout failure mode when FZ size is larger than 5.6 mm. According to equation (1), the minimum FZ size required to ensure that the pullout failure mode happens, for 1.2mm thick stainless steel sheet, is 4.38mm. However, as can be seen from Fig. 3, the critical weld size is well above the conventional FZ size recommendation given in equation (1).

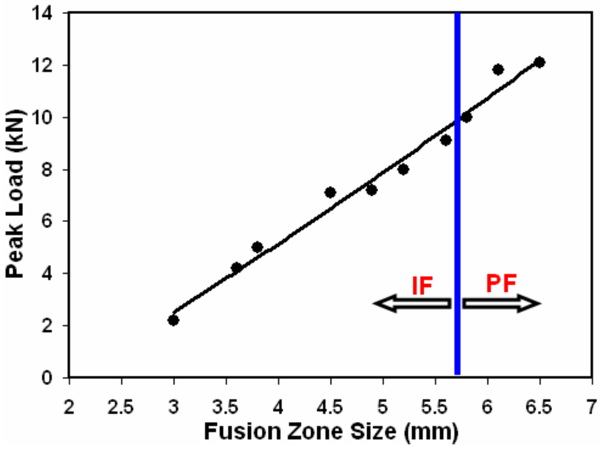


Fig. 3 Peak load versus FZ size. Interfacial failure to pullout failure transition is shown in this graph.

Failure mode analysis

In this section, a simple analytical model is proposed to predict joint failure mode during the tensile-shear testing of austenitic stainless steel resistance spot welds. Fusion zone size is the most important parameter determining stress distributions in sheet/sheet interface and weld nugget circumference. For small weld nuggets, before tensile stress causes necking shear stress reaches its critical value, as a result failure tends to occur under the interfacial failure mode. Therefore, in this section an attempt was made to estimate a minimum fusion zone size necessary to ensure nugget pullout failure mode during the tensile-shear test.

Considering nugget as a cylinder with (d) diameter and (2t) height , failure load at the interfacial failure mode (P_{IF}) could be expressed as equation (2) assuming uniform distribution of shear stress in the weld interface:

$$P_{IF} = \left(\frac{\pi d^2}{4}\right)\tau_{FZ} \qquad (2)$$

where: τ_{FZ} is the shear ultimate strength of the FZ.

In the pullout failure mode, it is assumed that failure occurs when maximum radial stress at the circumference of one half of the cylindrical nugget reaches the ultimate strength of the failure location. Therefore, equation (3) is suggested for the pullout failure of spot weld in the tensile-shear test.

$$P_{PF} = \pi dt\,(\sigma_{UTS})_{FL} \qquad (3)$$

where: $(\sigma_{UTS})_{FL}$ is the ultimate tensile strength of failure location. Note that in equation (3) thickness reduction due to indentation is neglected.

Failure is a competitive process, i.e. spot weld failure occurs in a mode which requires smaller force, i.e. force that will be first attained. A critical fusion zone size (d_{Cr}) can be defined which determines which one of the failure modes happens. Spot welds with $d<d_{Cr}$ tend to fail via interfacial failure and welds with $d>d_{Cr}$ tend to fail via nugget pullout failure mode.

Therefore, to obtain critical nugget diameter, d_{Cr}, equations (2) and (3) are intersected resulting in equation (4):

$$d_{Cr} = 4t\,\frac{(\sigma_{UTS})_{FL}}{\tau_{FZ}} \qquad (4)$$

Direct measurement of the mechanical properties of different regions of spot weld is difficult. It is reported [10] that there is a direct relationship between stainless steels tensile strength and their hardness. Also, shear strength of materials can be related linearly to their tensile strength by a constant coefficient, f. On that account, equation 4 can be rewritten as follows:

$$d_{Cr} = 4t\,\frac{H_{FL}}{f \times H_{FZ}} \qquad (5)$$

According to equation (5), the critical fusion zone size depends on the FZ and failure location hardness, in addition to sheet thickness. For a constant sheet thickness, decreasing the ratio of fusion zone hardness to failure location hardness raises its tendency to fail under the interfacial failure mode (i.e. larger d_{Cr}).

Fig. 4 shows the cross section of a sample failed through the pullout failure mode during the tensile-shear test. As can be seen, the location of the failure initiation of the austenitic stainless steel spot welds in the pullout mode is at HAZ, adjacent to the fusion zone. This can be attributed to the softening effect of grain growth in HAZ. Since, there is no significant change in hardness across the spot weld joint, stress concentration at FZ edge can also lead to failure at the FZ edge.

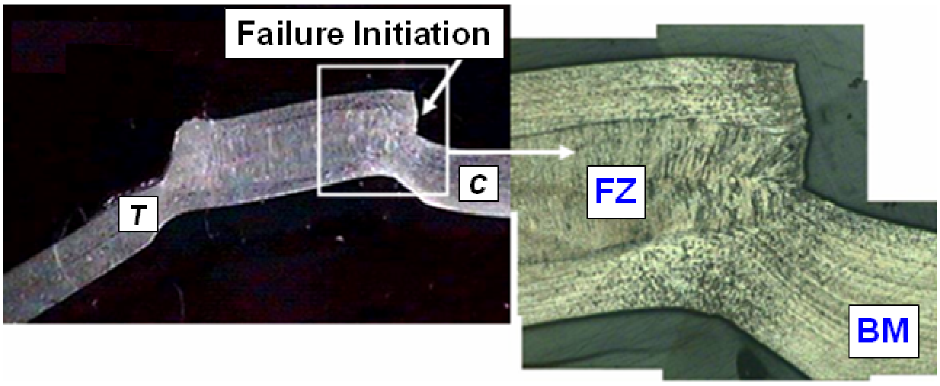


Fig. 4 Cross section of fracture surfaces of spot welds in tensile-shear test: T and C denote the leg subjected to tensile stress and leg subjected to compressive stress, respectively. One leg of the lower sheet and one leg of the upper are subjected to tensile stress.

It is reported that the ratio of the ultimate shear strength to ultimate tensile strength for 3xx stainless steel is about 0.75 [11]. In the case of AISI 304 stainless steel, average FZ hardness is approximately 200 HV and hardness of the softened zone in HAZ is about 175 HV. Therefore, the hardness ratio of FZ to failure location is about 1.14. By substituting these values in equation 5, critical fusion zone size is calculated to be 5.6mm. Fig. 3 shows that this value separates the interfacial and nugget pullout failure modes.

It is interesting to note that although, failure mode of low carbon resistance spot welds can be accurately predicted using conventional weld size recommendation of $d = 4\sqrt{t}$, it is not sufficient to ensure that the nugget pullout failure mode will happen during the tensile-shear test, when H_{FZ}/H_{FL} is low (e.g. in the case of austenitic stainless RSWs). Hardness of fusion zone of ferritic carbon steel is significantly higher than that of the base metal (H_{FZ}/H_{FL} is 2-3 depending on the chemical composition and the sheet thickness) because the dominant microstructure of the FZ is martensite [6]. The differences between hardness profiles of ferritic carbon steel and austenitic stainless steel result in different failure behaviors. Therefore, metallurgical factors including H_{FZ}/H_{FL} should be also considered to more precisely analyze and predict the failure mode of resistance spot welds.

Conclusions

1. Criterion for critical weld nugget diameter recommended of $4t^{0.5}$ is not sufficient to guarantee the pullout failure mode for AISI 304 resistance spot welds.
2. Failure location for AISI 304 RSW in pullout failure mode is at HAZ, adjacent to the weld nugget.
3. New analytical model for prediction of critical weld fusion zone size for AISI 304 spot welds is proposed. Apart from the plate thickness, minimum FZ size (d_{cr}) required to ensure pullout failure mode during the tensile-shear test, depends on hardness of the fusion zone, H_{FZ}, and hardness of failure location, H_{FL}.
4. According to this model, low fusion zone hardness to failure location hardness ratio increases the tendency of spot weld failure to occur in the interfacial failure mode during the tensile-shear test. Metallurgical characteristics of welds should be considered to predict and analyze the spot weld failure mode more precisely.

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