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Minimum fusion zone size required to ensure pullout failure mode of resistance spot welds during tensile-shear test

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Abstract

The effect of metallurgical factors (e. g. weld microstructure) on the failure mode of resistance spot welds is studied. In the light of failure mechanism of the spot welds, a simple analytical model is proposed to estimate minimum fusion zone size to ensure pull out failure mode of resistance spot welds during tensile-shear test. According to this model, ratio of fusion zone hardness to pullout failure location hardness and volume fraction of porosity in the fusion zone are the key metallurgical factors governing failure mode of spot welds during tensile-shear test, in addition to sheet thickness. Finally, the proposed model is compared with experimental results.

Key words: resistance spot welding (RSW), failure mode, fusion zone size

1. Introduction

Resistance spot welding (RSW) is considered as the dominant process for joining sheet metals in automotive industry. Typically, there are about 2000–5000 spot welds in a modern vehicle. The quality and mechanical behavior of resistance spot welds (RSW) significantly affect durability and crashworthiness of vehicle [1, 2].

Overload failure mode of spot welds is a qualitative measure of the weld reliability. Generally, spot welds fail in two modes: interfacial and pullout. In the interfacial mode, failure occurs via crack propagation through fusion zone (weld nugget), while in the pullout mode, failure occurs via complete (or partial) nugget withdrawal from one sheet. Failure mode of RSWs can significantly affect their load carrying capacity and energy absorption capability. Spot welds that fail in nugget pullout mode provide higher peak loads and energy absorption levels than spot welds that fail in interfacial and partial interfacial fracture modes. To ensure reliability of spot welds during vehicle lifetime, process parameters should be adjusted so that pullout failure mode is guaranteed [3, 4].

Weld nugget size 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/Society of Automotive Engineers [5] have recommended (Eq. (1)):

$$d = 4t^{1/2}, \tag{1}$$

where d and t are fusion zone size parameters in mm, respectively.

$4t^{1/2}$ rule works well for low carbon spot weld. However, this is not a proper criterion to ensure pullout failure mode of advanced high strength steel (AHSS) spot welds during tensile-shear test. One can find many evidences in literature indicating that to ensure pullout failure mode, a bigger weld nugget diameter is required compared with the recommended values by AWS. Results of Marya et al. [6] show that conventional recommendation of equation AWS is not sufficient to obtain pullout failure mode of DP600, DP780 and DP980 resistance spot welded. Also, Sun et al. [7] showed that $4t^{1/2}$ rule could not guarantee pullout failure mode of advanced high strength

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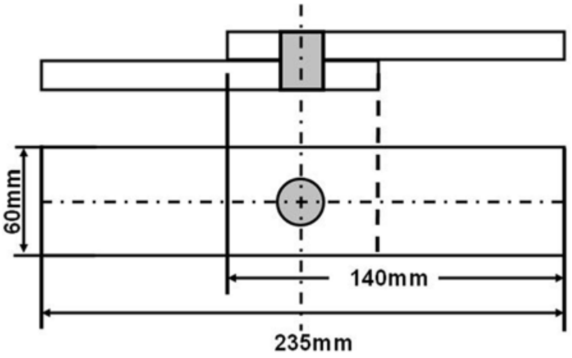

Fig. 1. Tensile-shear test sample dimension.

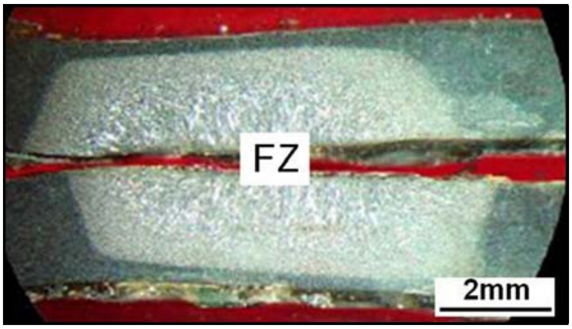

Fig. 2. Crack propagation through weld fusion zone in interfacial failure mode.

steel including DP800 and TRIP800. Therefore, it seems that metallurgical factors (e. g. weld microstructure) should be considered to more precisely analyze and predict the RSWs failure mode, in addition to sheet thickness. Previously some efforts were directed to develop sizing criteria for spot welds. In an early work by Janota [8], a sizing criterion was developed which was only a function of the sheet thickness. Thereafter, VandenBossche [9], Smith [10] and Chao [3] tried to develop sizing criteria, which were also functions of the materials properties, in addition to sheet.

In this paper, based on the experimental observation, an analytical mode is proposed to estimate minimum fusion zone size to ensure pullout failure mode of RSWs. Spot welds during their service life experience complex loading condition including shear, tensile, compression, bending and torsion stresses. In this work, however, the tensile-shear laboratory test was selected based on the fact that the RSWs show greater tendency to fail in interfacial failure mode during this loading condition in comparison to other ones such as peel test, coach peel test and cross tension [11]. Accordingly, failure mode during tensile-shear test is a conservative measure for quality control of spot welds. RSWs failed in pullout mode during tensile-shear test are expected to fail in pullout mode during cross-tension, peel and chisel tests. The proposed model accounts metallurgical factors including hardness characteristics of the weld and porosity level of the fusion zone. Finally, the results of this model are compared with experimental data and also with the results presented in the literature.

2. Experimental procedure

In this research, 2 mm thick low carbon steel, 2 mm thick HSLA steel and 2 mm thick DP980 were used as the base metals. Spot welding was performed using a 120 kVA AC pedestal type resistance spot welding machine, controlled by a PLC. Various welding variables were used to obtain various weld nugget size.

The static tensile-shear test samples were prepared according to ANSI/AWS/SAE/D8.9-97 standard [5]. Figure 1 shows the sample dimensions. Tensile-shear tests were performed at a cross head of 2 mm min^{-1} with an Instron universal testing machine. Failure mode was determined from the failed samples.

Samples for metallographic examination were prepared using standard metallography procedure. Optical microscopy was used to examine the microstructures and to measure physical weld attributes. After complete separation in the tensile-shear test failure location of samples was examined with optical microscope. Microhardness test was used to determine the hardness profile in horizontal directions (50 µm away from weld centerline), using a 100 g load on a Shimadzu microhardness tester.

3. Results and discussion

3.1. Failure mechanism

In this section, results of experimental investigation on the failure behavior of 2 mm thick low carbon resistance spot welds are presented. Similar failure behavior was observed for HSLA steel. Figure 2 shows cross section of failure path in interfacial failure mode. As can be seen, in interfacial failure the crack initiates in faying surface notch and propagates through the center of the fusion zone. The driving force for interfacial failure mode is shear stress at the weld centerline.

Figure 3a shows a typical macrograph of fracture cross section of spot welds which failed at pullout mode indicating the nugget is pulled out from upper sheet. The failure of the spot weld appears to be initiated near the middle of the nugget circumference in the *base metal* region. As can be seen, necking is the main failure mechanism in pullout failure mode. In the pullout failure mode, tensile stress is the driving force for necking [12, 13]. A similar failure mechanism was

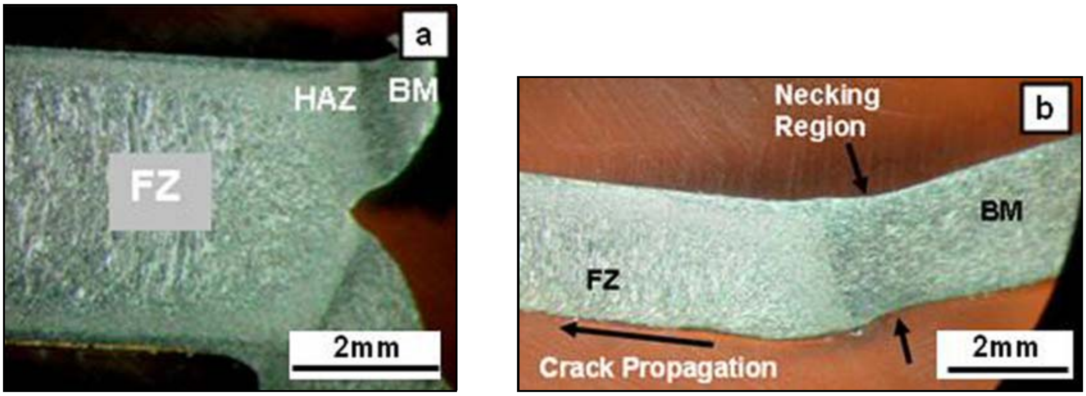

Fig. 3. a) A typical fracture cross section macrograph of a spot weld which is failed via pullout failure mode; b) Fracture cross section of a spot weld which is failed in the interfacial failure mode; necking is initiated in the base metal region, however, before its propagation in through-thickness direction, experienced shear stress at weld interface reaches its critical value at the weld interface. Consequently, spot weld failed in the interfacial mode.

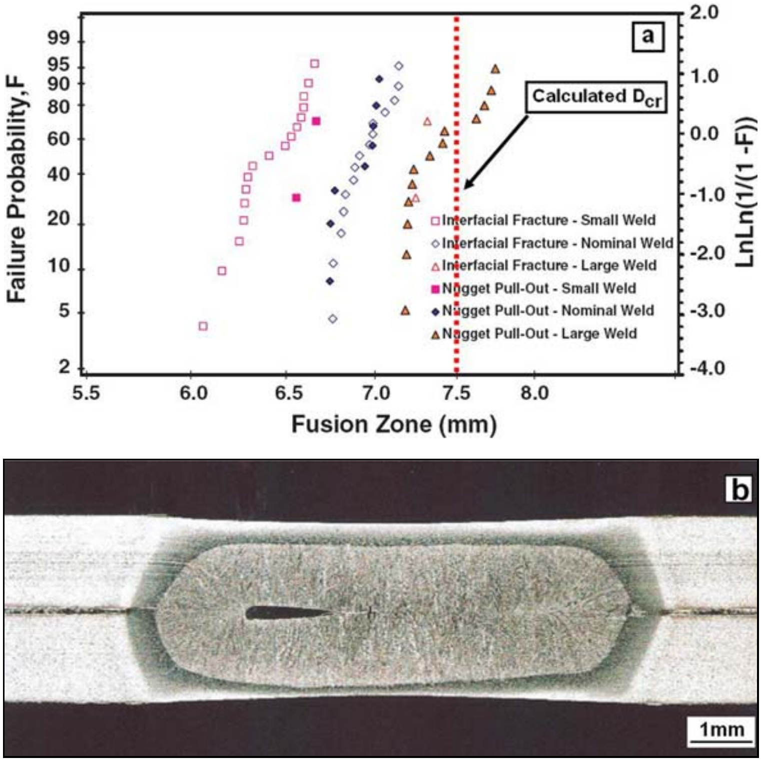

Fig. 4. a) Weld fusion zone size distribution and failure modes for the small, nominal and large TRIP800 weld populations [7], calculated D_{cr} is shown in the plot; b) Typical macrostructure of TRIP800 spot weld [7].

also observed in HSLA and DP600 steel tensile-shear specimens [14, 15].

Indeed, failure of low carbon resistance spot welds during tensile-shear test can be considered as a competition between crack propagation through fusion zone (i. e. interfacial failure) and necking in the base metal (i. e. pullout failure mode). This competition can be seen in Fig. 4b.

Weld nugget size is the most important parameter governing stress distribution. For small weld nuggets, shear stress reaches its critical value before tensile stress causes severe necking; therefore, failure tends to occur under interfacial failure mode.

3.2. Analytical model

Spot weld failure can be considered as a competition process between crack propagation through fusion zone (i. e. interfacial failure mode) and weld nugget pullout. Spot welds fail in one mode that requires less force. Therefore, in order to construct a model to predict failure mode, it is first necessary to develop two relations for calculating required force for each failure mode.

As described elsewhere [4, 11], driving force for interfacial failure is shear stress along two sheets' interface; while driving force for pullout failure is tensile stress around weld nugget. Each driving force has a critical value and the failure occurs in a mode, which reaches its critical value, sooner.

First, consider peak load of spot welds in interfacial mode. Considering nugget as a cylinder with (d) diameter and ($2t$) height, failure load at the interfacial failure mode (F_{IF}) can be expressed as Eq. (2):

$$F_{\mathrm{IF}} = \frac{\pi}{4} d^2 \tau_{\mathrm{WN}}, \tag{2}$$

where τ_{WN} is shear strength of the weld nugget.

Porosity in the weld center reduces spot weld load carrying capacity when spot weld fails in the interfacial failure mode. Consequently should be accounted for modeling of failure load in interfacial failure mode. Here, similar to Sun et al. [16] in modeling of failure load of Al spot weld under cross-tension test, in order to consider effect of weld nugget porosity on the peak load, a porosity factor (p) can be defined as follows:

$$p = \frac{A_{\mathrm{total}} - A_{\mathrm{porosity}}}{A_{\mathrm{total}}}, \quad 0 < p \leq 1, \tag{3}$$

where A_{total} is the total area of the fusion zone on the faying interface, and A_{porosity} is the projected area of porosity in the fusion zone on the faying interface of the weld. Therefore, Eq. (2) can be corrected as follows:

$$F_{\mathrm{IF}} = p \frac{\pi}{4} d^2 \tau_{\mathrm{WN}}. \tag{4}$$

Now, peak load of spot weld in pullout failure mode is considered. Pullout failure mode is accompanied by plastic deformation. When plastic deformation becomes large, finite deformation of the material near the nugget takes place and the specimen geometry changes significantly. It is obvious that a closed form analytical solution based on a plate or shell theory with the consideration of finite deformation and plastic deformation is difficult to obtain [15]. Here, simplified assumptions are considered to establish a simple relationship between failure load, sheet thickness and failure location strength of spot welds in pullout failure mode. It is assumed that in pullout failure mode, failure is initiated when maximum experiencing radial tensile stress at nugget circumference is reached to ultimate tensile strength of the failure location. Therefore, failure load in PF mode can be expressed as:

$$F_{\mathrm{PF}} = \pi \left(d + 2x\right) t \, \sigma_{\mathrm{FL}}, \tag{5}$$

where σ_{FL} is ultimate tensile strength of the pullout failure location and x is distance of pullout failure location from the fusion boundary. The results of the three-dimensional elastic-plastic finite element analysis of Satoh et al. [17] show that the maximum plastic strain is located at some distance in the order of the sheet thickness away from the nugget along the symmetric plane. As can be seen in Fig. 3a, distance of pullout failure location from fusion boundary is approximately equal to the sheet thickness (2 mm). Therefore, as a first approximation, x can be considered equal to the sheet thickness, when failure is located in the base metal region. When there is significant softening in the HAZ, x can be considered equal to HAZ size.

It should be noted again that based on the failure mechanism of spot welds under tensile-shear test, despite the global loading mode is shear, the failure has a tensile nature. This is why that ultimate tensile strength of failure location is used in Eq. (5).

Failure is a competitive process, i.e. spot weld failure occurs in a mode, which needs less force. To ensure pullout failure mode the following inequality should be satisfied:

$$F_{\mathrm{PF}} < F_{\mathrm{IF}}. \tag{6}$$

Therefore, to obtain the critical nugget diameter, d_{Cr}, Eqs. (4) and (5) are intersected resulting in Eq. (7):

$$d_{\mathrm{Cr}} = \frac{2t\sigma_{\mathrm{FL}}}{p\tau_{\mathrm{WN}}} \left[1 + \left(1 + \frac{2p\tau_{\mathrm{WN}} x}{t\sigma_{\mathrm{FL}}} \right)^{0.5} \right]. \tag{7}$$

Spot welds with $d < d_{\mathrm{Cr}}$ tend to fail via interfacial mode, as opposed to welds with $d > d_{\mathrm{Cr}}$ that tend to fail via the preferred pullout mode.

Direct measurement of the mechanical properties of different regions of spot weld is difficult. It is well known that there is a direct relationship between materials tensile strength and their hardness. Shear strength of materials can be related linearly to their tensile strength by a constant coefficient, *f*. Therefore, Eq. (7) can be rewritten as follows

$$d_{\mathrm{Cr}} = \frac{2t}{pfk} \left[1 + \left(1 + \frac{2pfkx}{t} \right)^{0.5} \right], \tag{8}$$

where k is the hardness ratio of the weld nugget to pullout failure location ($H_{\mathrm{WN}}/H_{\mathrm{FL}}$).

According to the model, in addition to sheet thickness, two key metallurgical factors governing failure mode of spot welds during tensile-shear test are:

i) Ratio of fusion zone hardness to pullout failure location hardness (k),

Table 1. Summary showing materials, hardness characteristics and failure mode of steels studied in the present work, predicted critical fusion zone size and AWS recommendation for weld nugget size

Material	t	p	FL	H_{BM}	H_{FL}	H_{WN}	$H_{\text{WN}}/H_{\text{FL}}$	Failure mode		Predicted d_{cr}	$d = 4\sqrt{t}$
								IF	PF		
LCS	2	1	BM	120	120	230	1.91	$d < 7.2$ mm	$d > 8.3$ mm	8.72	5.6
HSLA	2	1	BM	140	140	250	1.79	$d < 8.2$ mm	$d > 8.8$ mm	9.16	5.6

t – sheet thickness (mm), p – porosity factor, d – weld nugget size, FL – pullout failure location, H_{BM} – hardness of the base metal, H_{FL} – hardness of the pullout failure location, H_{WN} – hardness of the weld nugget, IF – interfacial failure, PF – pullout failure

ii) Porosity level (p).

$H_{\text{WN}}/H_{\text{FL}}$ ratio is controlled by chemistry and initial microstructure of the base metal and experienced cooling rate during welding. Porosity level of the fusion zone depends on the welding variables and chemical composition of the base metal.

3.3. Model verification

In this section, the proposed model is compared and verified with experimental results. To validate the model, various steels were spot welded. Microstructure and hardness profile of RSWs were examined. Thereafter, the samples were subjected to the tensile-shear test and failure modes of them were recorded. Also failure location of them was metallographically determined, as can be seen in Fig. 3.

For low carbon steel and HSLA steel, the failure locations in pullout failure were located in BM. It is reported that the ratio of the ultimate shear strength to ultimate tensile strength for steel is 0.7–0.8. Taking a similar approach, it is assumed here that the ultimate shear strength of the weld nugget is about 0.7 of its ultimate tensile strength. In the weld nugget no porosity was observed. Table 1 shows a summary of the results. As it can be seen, the proposed model can be considered as a first approximation for sizing weld fusion zone in order to obtain pullout failure mode during tensile-shear test.

For further validation, the results of the model were compared to the literature. Sun et. al. [7] investigated spot weld failure modes in tensile-shear test for DP800 and TRIP800 steels using the two-parameter Weibull distribution. Figure 4a shows weld fusion zone size distribution and failure modes for the small, nominal and large TRIP800 weld populations. As can be seen, the weld nugget size of $4t^{1/2}$ (~ 4.9 mm) is not sufficient to ensure nugget pullout under tensile-shear loading condition. Here, we use the proposed model to estimate required weld fusion zone size to ensure nugget pullout failure mode during tensile-shear test. According to data available in [7], hardness levels of the weld nugget and the base metal are about 500 and 250 HV, respectively. Softening was not observed in the HAZ of TRIP800 spot welds. Therefore, it can be deduced that pullout failure location will be in the base metal region. As mentioned above, as a first approximation, x can be considered equal to sheet thickness. According to Fig. 4b, the area percentage of porosity on the faying interface can be estimated as 20 %. Assuming the same level of $p = 0.80$ for all three populations, according to Eq. (8) for 1.5 mm TRIP800 steel sheet, d_{Cr} can be calculated as 7.5 mm. As can be seen, all of the spot welds with fusion zone size greater than 7.5 were failed in pullout failure mode.

Figure 5a shows the weld fusion zone size distribution and failure modes for the small, nominal and large DP800 weld populations. As can be seen, the weld nugget size of $4t^{1/2}$ (~ 5 mm) is not sufficient to ensure nugget pullout under tensile-shear loading condition. Again, we use the proposed model to estimate required weld fusion zone size to ensure nugget pullout failure mode during tensile-shear test. According to data available in [7], hardness levels of the weld nugget and the base metal are about 425 and 250 HV, respectively. Softening was observed in the HAZ of DP800 spot welds. Therefore, it can be deduced that pullout failure location will be in the HAZ softening zone. As mentioned above, as a first approximation, x can be considered equal to HAZ size. According to Fig. 4b, HAZ size is about 1 mm. Also, the area percentage of porosity on the faying interface can be estimated as 10 %. Assuming the same level of $p = 0.90$ for all three populations, according to Eq. (8) for 1.6 mm DP800 steel sheet, d_{Cr} can be calculated as 6.93 mm. As can be seen in Fig. 5a, most of the spot welds with fusion zone size greater than 6.93 mm failed in the pullout failure mode.

4. Conclusions

1. Critical weld nugget diameter recommended by AWS/ANSI/SAE is not sufficient to guarantee the pullout failure mode for AHSS steels.

2. According to the proposed model, low fusion zone hardness to failure location hardness ratio and presence of porosity within the weld nugget increases

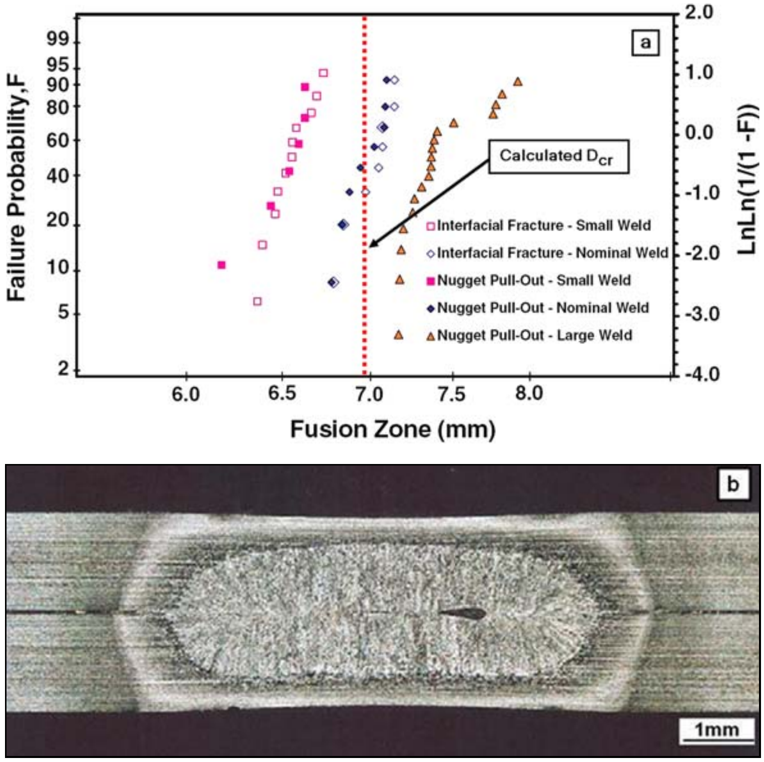

Fig. 5. a) Weld fusion zone size distribution and failure modes for the small, nominal and large DP800 weld populations [7], calculated d_{cr} is shown in the plot; b) Typical macrostructure of DP800 spot weld [7].

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.

3. The proposed model can serve as a first approximation for estimation the minimum fusion zone size to ensure pullout failure mode during tensile-shear test.

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