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FAILURE MODE OF M130 MARTENSITIC STEEL RESISTANCE-SPOT WELDS

NAČIN PORUŠITVE UPOROVNIH TOČKASTIH VAROV PRI MARTENZITNEM JEKLU M130

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This paper discusses the transition from the interfacial to the pullout failure mode for the M130 martensitic, advanced high-strength steel (AHSS) during a quasi-static tensile-shear test. It was studied whether the conventional/industrial weld-size criteria can produce pullout failure modes for M130 spot welds. The minimum fusion-zone size required to ensure the pullout failure mode during the tensile-shear test is estimated using an analytical model, taking into account the weld metallurgical characteristics, with good accuracy. Based on the theoretical analysis it was concluded that the failure-mode transition in M130 resistance-spot welds is influenced by the sheet thickness, the fusion-zone hardness and the intercritical heat-affected-zone hardness.

Keywords: martensitic steel, resistance-spot welds, failure mode, HAZ softening

Ta članek obravnava prehod od medploskovnega do iztrganega načina porušitve pri M130 martenzitnem naprednem visokotrdnostnem jeklu (AHSS) med kvazistatičnim natezno-strižnim preizkusom. Raziskano je bilo, ali je pri običajnih kriterijih industrijskih zvarov mogoče dobiti porušitev z iztrganjem pri točkastih zvarih M130. Z analitičnim modelom, ki upošteva metalurške značilnosti zvara, je bilo mogoče z dobro zanesljivostjo določiti minimalno področje zlivanja za porušitev z iztrganjem med natezno-strižnim preizkusom. Na podlagi teoretičnih analiz je bilo ugotovljeno, da na prehod načina porušitve pri M130 uporovno varjenih zvarih vplivajo debelina pločevine, trdota področja zlivanja in interkritična trdota toplotno vplivanega področja.

Ključne besede: martenzitno jeklo, uporovno varjeni zvari, način porušitve, mehčanje HAZ

1 INTRODUCTION

Advanced high-strength steels (AHSSs) have been introduced to vehicle designs in an effort to improve the collision-energy management and passenger safety, while maintaining or reducing the vehicle weight that, in turn, creates a better fuel economy.[1] Due to a very high strength and low formability, martensitic advanced high-strength steels (AHSSs) are good candidates for high-stiffness, load-transferring barriers and anti-intrusion barriers (e.g., A- and B-pillar reinforcements, rocker reinforcements, roof rails, front and rear bumpers, side-wall members, cross beams and door beams) improving crash management and protection of passengers during side-impact collisions.[2]

Resistance-spot welding is the predominant joining process in the automotive industry.[3–5] The failure mode of resistance-spot welds (RSWs) is a qualitative measure of mechanical properties.[4,5] **Figure 1** shows a schematic representation of the fracture surfaces in the main failure modes during a mechanical testing of the spot welds. Basically, spot welds can fail in two distinct modes described as follows:[6–11]

1. Interfacial failure (IF) mode, in which a fracture propagates through the fusion zone. It is believed that this failure mode has a detrimental effect on the crashworthiness of the vehicles.
2. Pullout failure (PF) mode, in which a failure occurs due to a withdrawal of the weld nugget from one sheet. In this mode, a fracture may be initiated in the BM, HAZ or HAZ/FZ depending on the metallurgical and geometrical characteristics of the weld zone

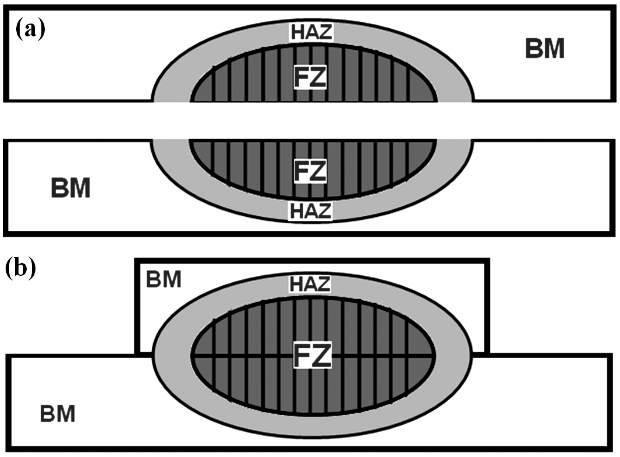

Figure 1: Schematic representation of: a) interfacial, b) pullout failure modes

Slika 1: Shematski prikaz načina porušitve: a) medploskovna, b) z iztrganjem and the loading conditions. Generally, the PF mode exhibits the most satisfactory mechanical properties.

Thus, vehicle crashworthiness, as the main concern in the automotive design, can be dramatically reduced if spot welds fail due to the interfacial mode. The pullout failure mode indicates, during a quality control, that the same weld would have indeed been able to transmit a high level of force, thus, causing a severe plastic deformation in its adjacent components and an increased strain-energy dissipation in crash conditions. Therefore, it is necessary to adjust the welding parameters so that the pullout failure mode is guaranteed.

The RSWs of AHSSs exhibit a higher tendency to fail in the interfacial failure mode than those of traditional steels (i.e., low-carbon and HSLA steels).[5–10] There are several size criteria for resistance-spot welds included in industrial standards. "The effectiveness of these criteria for evaluating AHSS spot welds, however, has not been adequately addressed in the automotive welding community; it was simply adopted from the mild steel practice and applied to AHSS spot welds".[12] The failure mode of the AHSS spot welds is a complex phenomenon causing an interaction among the geometrical factors, weld metallurgical properties and the loading mode. Consequently, it is necessary to develop a spot-weld sizing criterion based on the failure mode to reach a deeper understanding of the factors governing the failure mode of spot welds.

In this paper, the failure-mode transition of M130 martensitic steel resistance-spot welds under the tensile-shear loading condition is studied. The objectives of this study are:

1. to examine whether the existing weld-size criteria can produce the pullout failure mode for M130 spot welds;
2. to determine the critical fusion-zone size ensuring the pullout failure mode of M130 spot welds.

2 EXPERIMENTAL PROCEDURE

An M130 martensitic sheet with a thickness of 2 mm was used as the base metal in this study. The chemical composition and mechanical properties of the M130 used in this study are given in **Table 1**. Spot welding was performed using a 120 kVA AC pedestal-type resistance-spot welding machine, operating at 50 Hz and controlled by PLC. Welding was conducted using a 45°, truncated-cone, RWMA class 2 electrode with a face diameter 8 mm. To study the effects of the weld FZ size on the failure mode and mechanical properties, spot welding was performed in various welding conditions. The welding time, electrode force and electrode holding time after current-off were selected on the basis of the thickness of the base material and were kept constant at 0.5 s, 4.5 kN and 0.2 cycles. The welding current was changed step by step from 5 kA to 12.5 kA. The step size was 0.5 kA.

Table 1: Chemical composition and mechanical properties of the investigated M130 steel

Tabela 1: Kemijska sestava in mehanske lastnosti preiskovanega jekla M130

Chemical composition (*w*/%)					Tensile properties	
C	Mn	Si	S	P	YS* (MPa)	UTS** (MPa)
0.11	0.53	0.07	0.02	0.02	851	960

*Yield strength

** Ultimate tensile strength

The quasi-static tensile-shear test samples were prepared according to the ANSI/AWS/SAE/D8.9-97 standard.[13] **Figure 2a** shows the sample dimensions during the tensile-shear test. Since the tensile-shear specimen is asymmetrical, two shims with the same thickness were added at the grip sections of the specimen to ensure an alignment and to reduce the sheet bending and nugget rotation. The tensile-shear tests were performed at the cross-head speed of 2 mm/min with an Instron universal testing machine. The peak load and failure energy were extracted from the load-displacement curve (**Figure 2b**). The failure modes were determined by observing the weld fracture surfaces.

Microhardness test, a technique that has proven to be useful for quantifying the microstructure/mechanical property relationship, was used to determine the hardness profile. The hardness profile in the diagonal direction was obtained using the Vickers microhardness testing with an indenter load of 10 g and a speed of 10

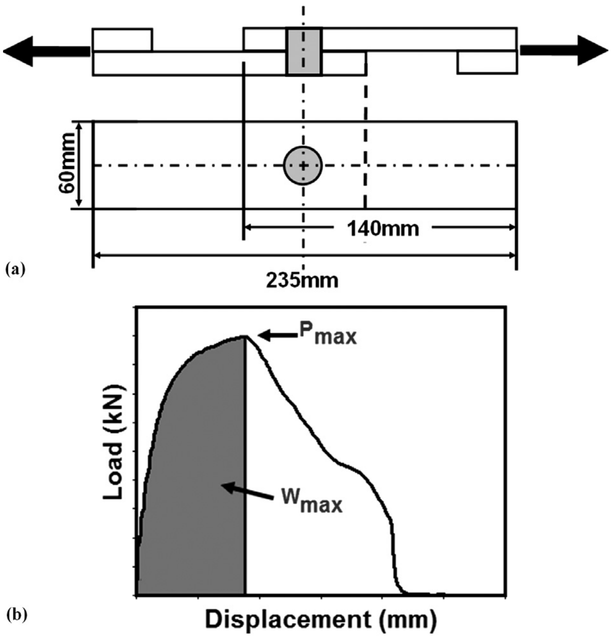

Figure 2: a) Tensile-shear specimen dimensions, b) a typical load-displacement curve with the extracted parameters; P_{max}: peak load, W_{max}: energy absorption

Slika 2: a) Dimenzije vzorcev za natezno-strižni preizkus, b) značilna krivulja obremenitev – raztezek s parametri; P_{max}: največja obremenitev, W_{max}: absorpcija energije indentations/min. The indentations were made on three paths with a 0.3 mm spacing.

3 RESULTS AND DISCUSSION

3.1 Hardness characteristics

Macrostructural characteristics of the RSWs, particularly the fusion-zone size, the microstructural and hardness characteristics, play important roles in their failure behavior and failure mode.[14–16] Rapid heating and cooling induced by the resistance-spot-welding thermal cycles significantly alter the microstructure in the joint zone. A typical macrostructure of M130 RSW is shown in **Figure 3a** indicating that there are distinct zones in the weldment including:

1. the fusion zone (FZ) or weld nugget, melted during the welding process and later resolidified, showing a cast structure. The macrostructure of the weld nugget consists of columnar grains;
2. the heat-affected zone (HAZ) that is not melted but it undergoes microstructural changes during welding;
3. the base metal (BM).

Figure 3b shows a typical hardness map of the M130 spot welds. The average hardness of the BM is about 300 HV. The average hardness of the FZ is 360 HV, which is about 1.2 times higher than the hardness of the BM. The microstructure of both BM and FZ is almost martensitic. Therefore, the higher hardness of the FZ, compared to the BM, can be related to the higher cooling rate during RSW. It has been reported that an increasing cooling rate can increase the dislocation density in the martensitic laths increasing its hardness.

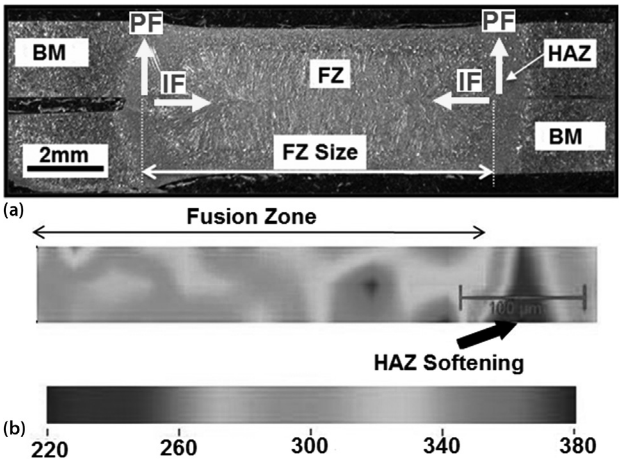

Figure 3: a) Typical macrostructure of M130 martensitic steel resistance-spot weld. Failure paths in the interfacial failure (IF) mode and pullout failure (PF) mode are also shown in the macrograph with the arrows. b) Typical hardness map

Slika 3: a) Značilna makrostruktura uporovnega točkastega zvara pri martenzitnem jeklu M130. S puščicami so prikazane poti porušitve pri medploskovni porušitvi (IF) in pri porušitvi z iztrganjem (PF). b) Značilna razporeditev trdote

A reduction in the hardness (softening), with respect to the BM, was observed in the HAZ. The minimum hardness of the HAZ is about 215 HV (i.e., the maximum hardness reduction of 85 HV). The observed softening can be related to the following reasons:

1. In the intercritical HAZ (ICHAZ) region, the peak temperature is ranging between A_{c1} and A_{c3} and the BM microstructure transforms into ferrite plus austenite during heating. Due to the fast welding cooling rates, austenite can subsequently transform into martensite. Therefore, the formation of an allotriomorphic ferrite phase in the ICHAZ leads to a hardness reduction with respect to the fully martensitic BM.
2. In the subcritical HAZ (SCHAZ), the peak temperature is below A_{c1} resulting in tempering of the metastable martensite. This issue causes a reduction in the hardness with respect to the BM.

3.2 Failure-mode analysis

Figure 4 shows the effect of the FZ size on the failure mode of M130 welds. As can be seen, the increasing FZ size alters the failure mode from the interfacial to the pullout mode. There is a critical FZ size, above which the pullout failure mode is guaranteed. According to **Figure 4**, the minimum FZ size of 9.2 mm is required to ensure the PF mode.

In order to study the effect of the failure mode on the mechanical performance of M130 resistance-spot welds, box plots of peak load and energy absorption are shown in **Figures 5a** and **5b**, respectively. As can be seen in **Figure 5**, the average peak load of those spot welds that failed in the IF is lower than the peak load of the spot welds that failed in the PF mode. Therefore, due to its significant impact on the joint reliability, the failure mode has been an interesting issue of some recent studies. The transition from the IF mode to the PF mode is generally related to the increase in the FZ size above the

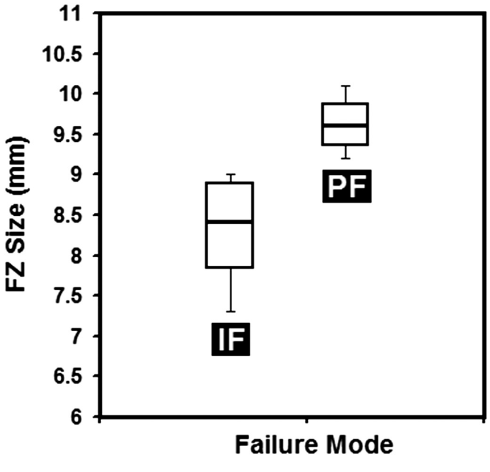

Figure 4: Effect of the FZ size on the failure mode of M130 martensitic steel resistance-spot welds

Slika 4: Vpliv velikosti FZ na način porušitve uporovnega točkastega zvara pri martenzitnem jeklu M130

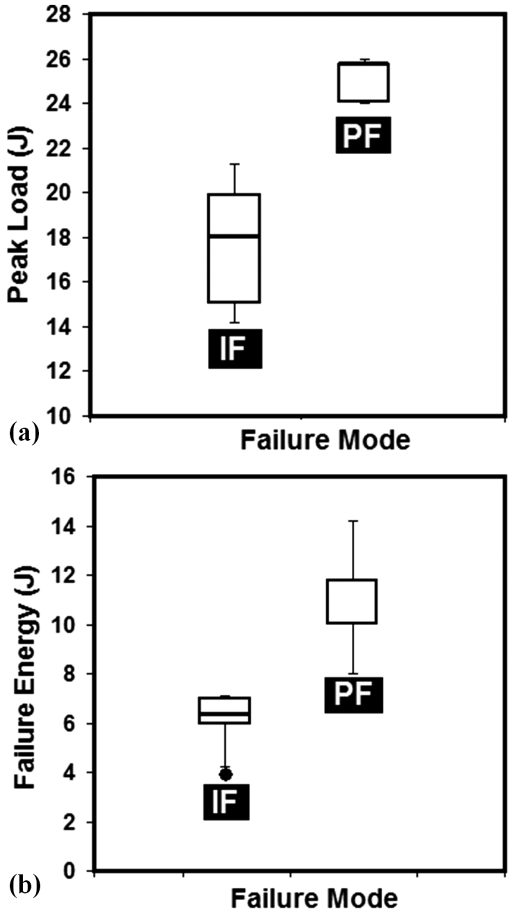

Figure 5: Box plots of: a) peak load (P_{max}) and b) failure energy (W_{max}) versus failure mode for M130 martensitic steel resistance-spot welds

Slika 5: Prikaz: a) največje obremenitve (P_{max}) in b) energije porušitve (W_{max}) glede na način porušitve točkasto uporovno varjenih zvarov martenzitnega jekla M130

minimum value. In the following sections, the failure-mode transition is compared with the existing criterion for the weld-nugget sizing of a spot weld. For practical purposes, it is interesting to compare the experimentally determined minimum FZ size required to obtain the PF mode with the existing industrial standards for weld-nugget sizing. Various industrial standards have recommended a minimum weld size for a given sheet thickness:

1. According to AWS/ANSI/AISI,[12] the weld-button sizing used to ensure that the weld size was large enough to carry the desired load, is based on equation (1):

$$D = 4t^{0.5} \tag{1}$$

where D is the weld-nugget size and t is the sheet thickness (mm).

2. According to the Japanese JIS Z3140[17] and German DVS2923[18] standards the required weld size is specified according to equation (2):

$$D = 5t^{0.5} \tag{2}$$

3. The minimum weld-nugget size (equation 3) and the nominal weld size (equation 4) are also frequently used in certain industries:[19]

$$D = 0.69\ (1.65t - 0.007)^{0.5} \tag{3}$$

$$D = 0.86\ (1.65t - 0.007)^{0.5} \tag{4}$$

Figure 6 compares the experimentally determined critical FZ size for the spot welds made on M130 steel 2 mm and the weld size recommended by the industry. As can be seen, the most common weld-sizing criteria of $4t^{0.5}$ and $5t^{0.5}$ are not sufficient to produce a weld with the PF mode. Also, equation (3) and equation (4) are not sufficient to avoid the interfacial failure. Despite the fact that the industrial recommendations work well for obtaining the pullout mode of low-carbon steels, the sizing based on these recommendations does not guarantee the PF mode during the tensile-shear testing of the AHSS spot welds. This is due to the fact that these recommendations ignore the effect of metallurgical factors on the failure mode so that these models include only the sheet thickness for the sake of simplicity. Radakovic and Tumuluru[20] used finite-element modeling to predict the resistance-spot-weld failure mode and the loads in the shear-tension tests of advanced high-strength steels (AHSS). In the finite-element model, the base material, the heat-affected zone and the fusion-zone properties were assumed to be homogeneous. According to their finite-element modeling results, the critical fusion-zone size can be expressed as follows:

$$D_C = 4t \tag{5}$$

According to their results, the critical weld size for a thick sheet 2 mm is 8 mm. However, the experimental value for a thick M130 2 mm is 9.2 mm, which is above the recommended value of this mode. Indeed, this model assumes the mechanical properties across the weldment to be homogenous and does not take into account the HAZ softening. In the following section an analytical

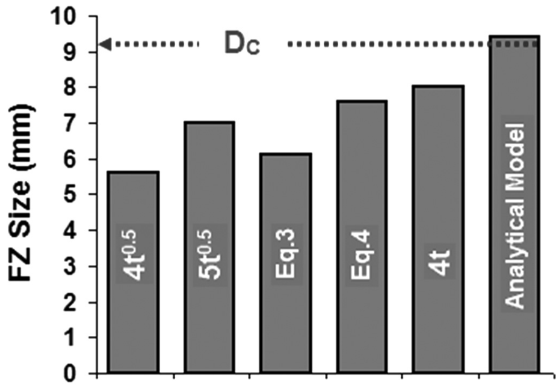

Figure 6: Comparison of the experimentally determined critical FZ zone (D_C) for M130 steel 2 mm with the thickness-based recommendations. The predicated value of D_C obtained with the analytical model is also shown.

Slika 6: Primerjava eksperimentalno določenega kritičnega področja FZ (D_C) za jeklo M130 s priporočljivo debelino. Prikazana je tudi napovedana vrednost za D_C, dobljena z analitičnim modelom.

model considering the weld hardness characteristics is used to determine the critical FZ size to ensure the pullout failure mode.

3.3 Prediction of the failure mode taking into account metallurgical factors

The failure of the resistance-spot welds during the tensile-shear test can be described as a competition between the shear plastic deformation of the fusion zone (i. e., the IF mode) and the necking of the base metal or HAZ (i. e, the PF mode).[11,16] Spot welds usually fail in the mode requiring less force during a fracture. It is well documented that the driving force for the IF is the shear stress along the sheet/sheet interface, while the driving force for the PF is the tensile stress around the weld nugget.[11,16] In order to develop a model that predicts the failure mode, the first necessary step is to develop the equations for calculating the required force for each failure mode.

First, we have to consider the peak load of the spot welds in the interfacial mode. Considering the nugget as a cylinder with a specific (D) diameter and ($2t$) height, the failure load of the interfacial failure mode (F_{IF}) can be expressed with equation (6):

$$F_{\mathrm{IF}} = \pi/4\ D^2\tau_{\mathrm{FZ}} \tag{6}$$

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

Now, the peak load of the spot weld in the pullout failure mode is considered. It is assumed that, in the pullout failure mode, the failure is initiated when the maximum experienced radial tensile stress at the nugget circumference reaches the ultimate tensile strength of the failure location. Therefore, the failure load in the PF mode can be expressed as:

$$F_{\mathrm{PF}} = \pi\ Dt\sigma_{\mathrm{PFL}} \tag{7}$$

where σ_{PFL} is the ultimate tensile strength of the pullout failure location. In the case of M130, where there is significant softening in the ICHAZ, the peak load in the PF mode can be expressed as follows:

$$F_{\mathrm{PF}} = \pi\ Dt\sigma_{\mathrm{ICHAZ}} \tag{8}$$

where σ_{ICHAZ} is the tensile strength of the ICHAZ. To obtain the critical nugget diameter, D_{C}, equations (6) and (8) are intersected resulting in equation (9):

$$D_{\mathrm{C}} = 4t\sigma_{\mathrm{ICHAZ}}/\tau_{\mathrm{FZ}} \tag{9}$$

The spot welds with $D < D_{\mathrm{C}}$ tend to fail via the interfacial mode, contrary to the welds with $D > D_{\mathrm{C}}$ that tend to fail via the preferred pullout mode.

A direct measurement of the mechanical properties of different regions of a spot weld is difficult. It is well known that there is a direct relationship between the tensile strength of a material and its hardness. The shear strength of a material can be related linearly to its tensile strength using a constant coefficient, f. Therefore, equation 9 can be rewritten as follows:

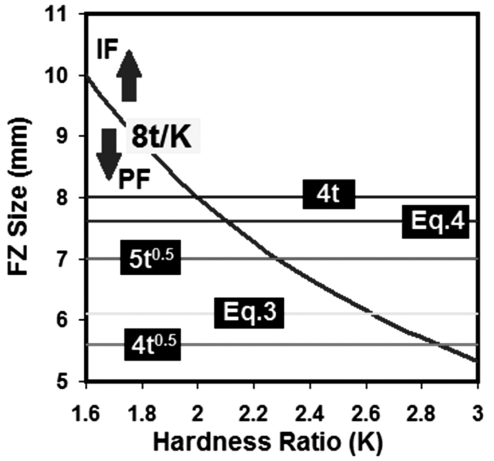

Figure 7: Comparison of the mode prediction and thickness-based recommendations when the sheet thickness (t) is 2 mm. The hardness ratio (K) is defined as the ratio of the FZ hardness to the pullout-failure-location hardness.

Slika 7: Primerjava napovedane vrste porušitve in priporočil debeline, če je debelina pločevine (t) 2 mm. Razmerje trdote (K) je določeno kot razmerje trdote FZ in lokalne trdote pri iztrganju.

$$D_{\mathrm{C}} = 4tH_{\mathrm{ICHAZ}}/fH_{\mathrm{FZ}} \tag{10}$$

Now, to validate the model, the experimental results are compared with the analytical results. In the case of the M130 martensitic steel, the average FZ hardness is approximately 380 HV and the hardness of the softened zone in the ICHAZ is about 225 HV. Therefore, the hardness ratio of the FZ to the failure location is about 1.68. According to the Tresca criteria, the ratio of the ultimate shear strength to the ultimate tensile strength, f, is 0.5. By substituting these values in equation (10), the critical fusion-zone size is calculated to be 9.4 mm. Figure 6 shows that this value is a reasonable estimation of the critical FZ size.

Figure 7 compares the analytical model and the existing criteria for a sheet 2 mm. As can be seen, the sizing based on $4t^{0.5}$, Eq.3, $5t^{0.5}$, Eq.4 and $4t$ criteria is not appropriate for obtaining the PF mode when the hardness ratios are smaller than 2.85, 2.65, 2.3, 2.1 and 2, respectively. As the hardness ratio is reduced, the discrepancy between the analytical model and the industrial sizing criteria is increased.

4 CONCLUSIONS

In this work, the failure-mode transition of M130 martensitic resistance-spot welds is investigated. The following conclusions can be drawn from this work:

1. A reduction in the hardness (softening), with respect to the BM, was observed in the HAZ. The heat-affected-zone softening reduced the strength of the HAZ, resulting in the strain localization and, hence, causing the PF mode.
2. There is a critical FZ size ensuring the pullout failure mode during the tensile-shear test. According to the

theoretical analysis presented in this study, the failure-mode transition of the M130 spot welds is governed by the sheet thickness, FZ hardness and ICHAZ hardness.

3. The existing industrial weld-nugget sizing criteria are not sufficient to ensure the pullout failure mode during the tensile-shear testing of the M130 resistance-spot welds. The proposed model can predict the failure mode with good accuracy.

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