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DP780 DUAL-PHASE-STEEL SPOT WELDS: CRITICAL FUSION-ZONE SIZE ENSURING THE PULL-OUT FAILURE MODE

TOČKASTI ZVARI JEKLA DP780 Z DVOFAZNO STRUKTURO: KRITIČNA VELIKOST STALJENE CONE, KI ZAGOTAVLJA PORUŠENJE Z IZPULJENJEM

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This paper addresses the transition from the interfacial to the pull-out failure mode for DP780 dual-phase-steel resistance spot welds under tensile-shear and cross-tension loading conditions. It was studied whether industrial weld-size criteria can produce pull-out failure modes. Based on the failure mechanism of the spot welds in a cross-tension test, a simple analytical model is proposed to predict the critical FZ size to ensure the pull-out failure mode. According to the findings, the sheet thickness, the hardness ratio of the fusion zone to the sub-critical heat-affected zone, the amount of shrinkage voids in the fusion zone and the width of the HAZ are the main controlling factors for the transition from the interfacial to the pull-out failure mode in cross-tension loading. The fusion-zone size was proved to be the key factor controlling the cross-tension and tensile-shear strengths of DP780 resistance spot welds.

Keywords: advanced high-strength steel, resistance spot welding, failure mode

Ta članek obravnava prehod iz medploskovne porušitve v porušitev z izpuljenjem pri uporovnih točkastih zvarih dvofaznega jekla DP780 med natezno-strižnim in prečnim obremenjevanjem. Ugotovljeno je bilo, da lahko kriterij industrijske velikosti zvarov povzroči porušitev z izpuljenjem. Na osnovi mehanizma porušitve točkastih zvarov je predlagan enostaven model za napovedovanje kritične velikost FZ, ki zagotavlja način porušitve z izpuljenjem. Glavni kontrolni faktorji za prehod iz medploskovne v porušitev z izpuljenjem pri prečni obremenitvi so debelina pločevine, razmerje trdote v talilni coni in v podkritični toplotno vplivani coni, količina praznin zaradi krčenja v talilni coni in širina HAZ. Širina talilne cone se je izkazala kot ključni faktor, ki kontrolira strižno in prečno natezno trdnost uporovnih točkastih zvarov pri DP780.

Ključne besede: napredno visokotrdnostno jeklo, uporovni točkasti zvar, način porušitve

1 INTRODUCTION

Due to a combination of excellent strength and proper formability, advanced high-strength steels (AHSSs) have a potential for improvement in the vehicle crash performance without an addition of excess weight.[1] Ferrite-martensite dual-phase (DP) advanced high-strength steels are currently used in the automotive industry. In this combination of two phases, martensite contributes its high strength and a ferrite matrix provides good elongation, creating a good combination of strength and ductility for the applications that require good formability. This unique composite microstructure has other interesting mechanical properties such as continuous yielding, a low ratio of the yield stress to the tensile strength and a high initial work-hardening rate.[2–4] However, higher alloying contents of these steels limit their weldability and the thermal cycle of a welding process destroys a carefully designed microstructure which deteriorates the mechanical properties of the weld.[5]

Resistance spot welding (RSW) is a vital joining process for the automotive production. Typically, there are about 2000–5000 spot welds in a modern vehicle. Automotive structural assemblies use groups of spot welds to transfer load through the structure during a crash. Additionally, spot welds can act as fold-initiation sites to manage impact energy.[6] Vehicle crashworthiness, which is defined as the capability of a car structure to provide adequate protection to its passengers against injuries in the event of a crash, largely depends on the integrity and the mechanical performance of the spot welds.[7–9] Failure of spot welds may affect the vehicle's stiffness and NVH (noise, vibration and harshness) performance at the general level.[10] Therefore, the quality, performance and failure characteristics of resistance spot welds are important for determining the durability and safety design of vehicles.

The mode in which resistance spot welds fail can significantly affect their load-carrying capacity and energy-absorption capability. Generally, a resistance-spot-weld failure occurs in two modes: interfacial failure (IF) and pull-out failure (PF).[11–13] **Figure 1** shows a schematic representation of the failure modes of resistance spot welds. The interfacial failure mode propagates along the

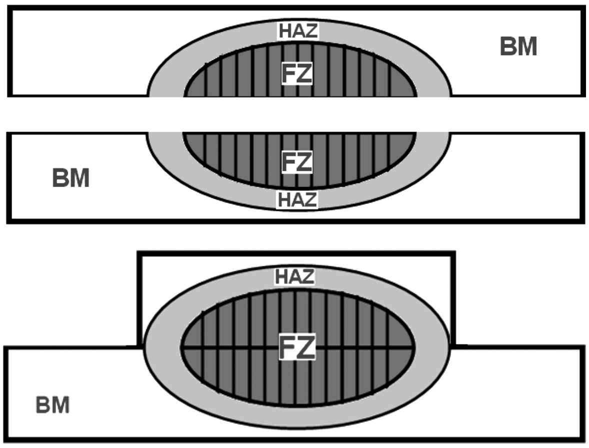

Figure 1: Schematic representation of typical failure modes that can occur during mechanical testing: a) interfacial, b) pull-out

Slika 1: Shematska predstavitev značilnih porušitev, do katerih pride med mehanskim preizkušanjem: a) medploskovna, b) izpuljenje

centerline of a weld nugget, resulting in a sudden low-ductility failure. Because of its low ductility, the IF is generally considered an undesired failure mode for spot welds; hence, the IF mode is detrimental to weldability.[5] The resistance spot welds of the AHSS exhibit a higher tendency to fail in the interfacial failure mode than those of traditional steels (i.e., low-carbon and HSLA steels). Due to its significant impact on the joint reliability, the failure mode has been an interesting issue for some recent studies. The transition from the IF mode to the PF mode is generally related to the increase in the size of the fusion zone above the minimum value.[5,14–19] There are several sizing criteria for resistance spot welds including industrial standards. The effectiveness of these criteria for evaluating an AHSS spot weld, however, was not adequately addressed in the automotive welding community; it was simply adopted from the mild-steel practice and applied to AHSS spot welds.[19] The failure mode of the AHSS spot welds is a complex phenomenon which involves interactions among 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 obtain an in-depth understanding of the factors governing the failure mode of spot welds.

In this paper, the microstructure and the failure mode of DP780 resistance spot welds under cross-tension and tensile-shear loading conditions are studied. The objectives of this study are: 1) to examine whether the existing weld-size criteria can provide for the pull-out failure mode of the DP780 spot welds; 2) to investigate the transition from the interfacial to the pull-out failure mode using both experimental and analytical approaches.

2 EXPERIMENTAL PROCEDURE

DP780 dual-phase steel sheets 2 mm thick were used as the base metal. **Table 1** shows the chemical composition and tensile properties of the investigated steel. Resistance spot welding was performed using a 120 kV A AC pedestal-type resistance-spot-welding machine, controlled with a PLC operating at 50 Hz. The welding was conducted using a 45-deg truncated-cone RWMA Class 2 electrode with an face diameter 8 mm.

Table 1: Chemical composition and mechanical properties of the investigated DP780 dual-phase steel in mass fractions, *w*/%

Tabela 1: Kemijska sestava in mehanske lastnosti preiskovanega dvofaznega jekla DP780 v masnih deležih, *w*/%

Chemical composition					Tensile properties	
C	Mn	Si	Cr	Mo	TUS* (MPa)	EL**
0.16	0.67	0.24	0.04	0.01	820	14

*Yield strength, **Elongation

To study the effects of the welding conditions on the weld performance, several welding schedules were used. The electrode force and the holding time were selected on the basis of the thickness of the base material and kept constant at 5.1 kN and 0.2 s, respectively. The welding current was increased step by step from 7 kA to 11.5 kA at the welding times of 0.5 s. The welding parameters were chosen below the expulsion limit to avoid the undesirable failure mode. Seven samples were prepared

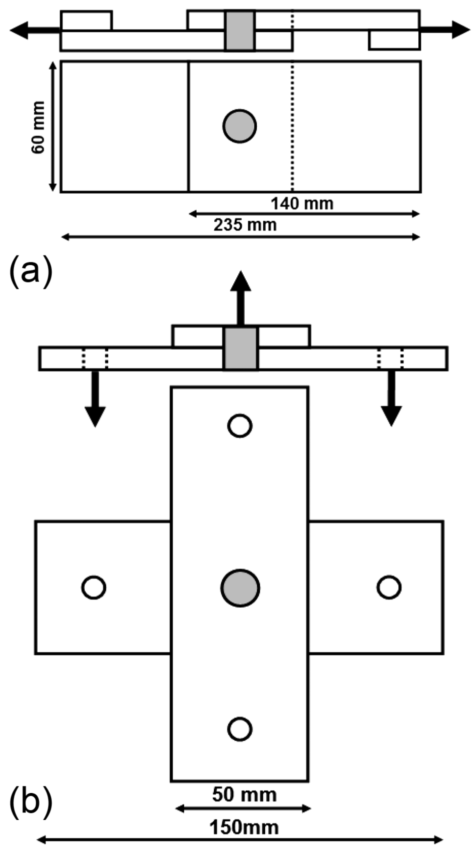

Figure 2: Test configuration and sample dimensions: a) tensile-shear test, b) cross-tension test

Slika 2: Izvedba preizkusov in dimenzije vzorcev: a) natezni strižni preizkus, b) prečni natezni preizkus for each welding condition including three samples for the tensile-shear test, three samples for the cross-tension test and one sample for a metallographic investigation and measurement of the weld size.

The samples for the mechanical testing were prepared according to the AWS standard.[20] **Figure 2** shows the sample dimensions for the tensile-shear test and cross-tension test. The mechanical tests were performed at a cross head of 10 mm/min with an Instron universal testing machine. The failure modes of the spot-welded specimens were determined by examining the fractured samples. The fracture surfaces of the samples were examined with scanning electron microscopy (SEM).

Weld-nugget (fusion-zone) sizes were measured for all the samples on the metallographic cross-sections of the welds. A Vickers microhardness test was performed using an indenter load of 100 g for a period of 20 s to obtain the diagonal hardness profile from the center of the FZ to the BM. The hardness indentations were spaced 0.3 mm apart.

3 RESULTS AND DISCUSSION

3.1 Failure mode

The failure modes of the samples were identified by examining the fracture surfaces. For the tensile-shear (TS) samples, it was observed that all the spot welds failed in the interfacial failure mode. On the other hand, both interfacial and pull-out failure modes were observed during the cross-tension (CT) loading (**Figures 3a** and **3b**). **Figure 3c** shows the fracture surface of a weld failed in the IF mode demonstrating a cleavage-type fracture which indicates a low-fracture energy. Therefore, it is necessary to adjust the welding parameters so that obtaining the PF mode is guaranteed. The fracture surfaces of the spot welds failed in the IF mode exhibit some voids. An examination of the surface near the voids (**Figure 3d**) revealed a dendritic fracture surface indicating that these voids/cracks were formed due to solidification shrinkage.

It is well documented that the size of the fusion zone is the key physical weld attribute controlling the failure-mode transition of spot welds.[5,12–19] The effect of the welding current on the FZ size is shown in **Figure 4** indicating an enlargement of the weld nugget by increasing the welding current and generating a higher heat at the sheet/sheet interface. According to **Figure 4**, the failure mode during the CT loading was changed from the IF to the PF by increasing the welding current and the FZ size. In order to avoid the IF mode during the cross-tension test, the minimum welding current of 9 kA should be used for welding a DP780 steel sheet. The minimum FZ size required to obtain the PF mode during the CT loading was 6.6 mm. However, all the spot welds made with the welding current ranging from 7 kA to 11.5 kA and with the FZ size ranging from 3.4 mm to 9.2 mm failed in the IF mode indicating a higher tendency to the interfacial failure during the TS loading compared with that occurring during the CT loading.

Due to its significant impact on the joint reliability, the failure mode has been an interesting issue for some recent studies. The transition from the IF mode to the PF

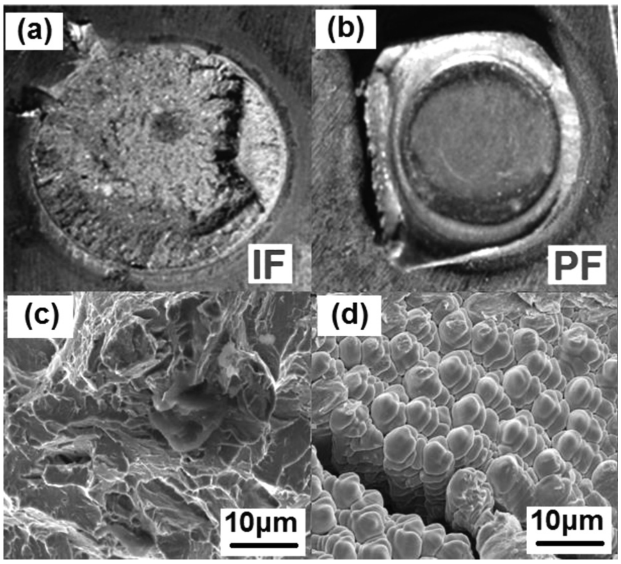

Figure 3: a) Typical interfacial-failure (IF) surface during cross-tension test, b) typical pullout failure (PF) during cross-tension test, c) SEM of fracture morphology of the spot welds failed in IF mode, d) morphology of solidification void found in the fracture surface of welds failed in IF mode

Slika 3: a) Značilna ploskev medploskovne porušitve (IF) med prečnim nateznim preizkusom, b) značilna porušitev z izpuljenjem (PF) med prečnim nateznim preizkusom, c) SEM-posnetek morfologije preloma točkastega zvara, porušenega v IF načinu, d) videz praznine pri strjevanju na površini preloma zvara, porušenega v IF načinu

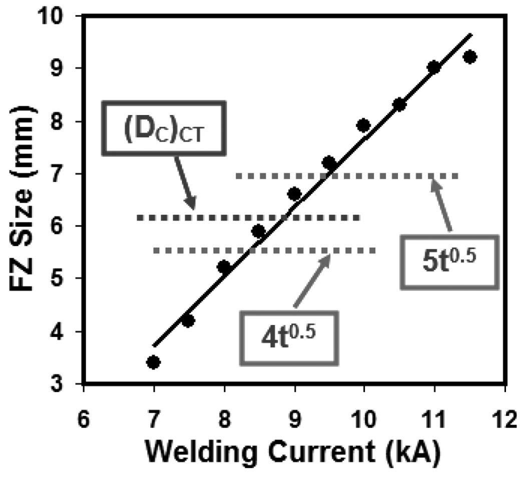

Figure 4: Effect of welding current on FZ size of DP780 resistance spot welds. Transition from interfacial to pull-out failure mode for CT loading is also shown. All spot welds were failed in IF mode during TS loading. Conventional weld-sizing recommendations of $4t^{0.4}$ and $5t^{0.4}$ and calculated $(D_C)_{CT}$ are also superimposed.

Slika 4: Vpliv varilnega toka na velikost FZ v uporovnem točkastem zvaru DP780. Prikazan je tudi prehod iz medploskovne v porušitev z izpuljenjem pri CT-obremenitvi. Vsi točkasti zvari so bili porušeni v načinu IF pri TS-obremenitvi. Nadgrajena so tudi priporočila za velikost zvara $4t^{0,4}$, $5t^{0,4}$ in izračunan je $(D_C)_{CT}$.

mode is generally related to the increase in the size of the FZ above the minimum value. In the following sections, the failure-mode transition is compared with the exiting criterion for sizing the weld nugget of a spot weld.

3.1.1 Industrial recommendations

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 recommend the minimum weld size for a given sheet thickness:

(I) AWS/ANSI/AISI[20] determines the weld-button sizing to ensure that the weld size is large enough to carry the desired load, on the basis of Equation (1):

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

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

(II) According to Japanese JIS Z 3140[21] and German DVS 2923[22] standards the required weld size is specified with Equation (2):

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

According to **Figure 4**, the weld-sizing criterion of $4t^{0.5}$ is not sufficient to produce a weld with the PF mode during the TS and CT loading. Neither can the sizing of spot welds based on the $5t^{0.5}$ criterion produce welds with the PF mode during the TS loading. However, the weld-sizing criterion of $5t^{0.5}$ is sufficient to produce a weld with the PF mode during the CT loading.

3.1.2 Chao model

On the basis of the competition between the shear plastic deformation in the nugget circumference (i.e., the nugget pullout) and the crack propagation in the weld nugget (i.e., the interfacial failure mode), Chao[23] derived the equation for the critical weld-nugget size for the cross-tension test as follows:

$$D_C = 2.93\left(\frac{\tau_{yBM}}{K_C^{FZ}}\right)^{2/3} t^{4/3} \tag{3}$$

where τ_{yBM} is the shear strength of the base metal and K_C^{FZ} is the fracture toughness of the fusion zone. τ_{yBM} and K_C^{FZ} can be obtained from the experimental data. Although Chao relates the critical weld size to the fracture toughness of the weld nugget and the fracture strength in the shear of the HAZ, he tried to show that his model is not material dependent. He suggested the following formula:

$$D_C = 3.41t^{4/3} \tag{4}$$

According to Equation (4), the minimum FZ size required to ensure the PF mode during the tensile-shear testing of 2 mm DP780 welds is 8.6 mm. According to **Figure 4**, the sizing based on this criterion can avoid the interfacial failure mode; however, the recommended value is overestimated by nearly 30 % above the required weld size.

In the following sections the transition behavior during the TS and CT are explained in the light of the failure mechanism. It will be seen that the transition of the IF to the PF mode is governed by the fusion-zone size, the hardness characteristics of the welds and also by the loading condition.

3.1.3 New model for estimating the critical FZ size during the CT loading

Figure 5 shows a simple model describing the stress distribution at the interface and circumference of a weld nugget during the CT test. According to **Figure 5**, the driving force for the IF is the tensile stress along the sheet/sheet interface, while the driving force for the PF is the shear stress around the weld nugget. For small weld nuggets, before the shear stress causes the nugget pullout, the tensile stress at the sheet/sheet interface reaches its critical value; as a result, the failure tends to occur in the interfacial failure mode. Therefore, in this section, a model is proposed to estimate the minimum fusion-zone size necessary to ensure the nugget pull-out-failure mode during the cross-tension test. 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 to happen.

Considering the nugget as a cylinder with a certain diameter (D), the failure load in the interfacial failure mode during the cross-tension test, $(P_{IF})_{CT}$, can be expressed with Equation (5):

$$(P_{IF})_{CT} = \frac{\pi D^2}{4}\sigma_{FZ} \tag{5}$$

where σ_{FZ} is the tensile strength of the FZ.

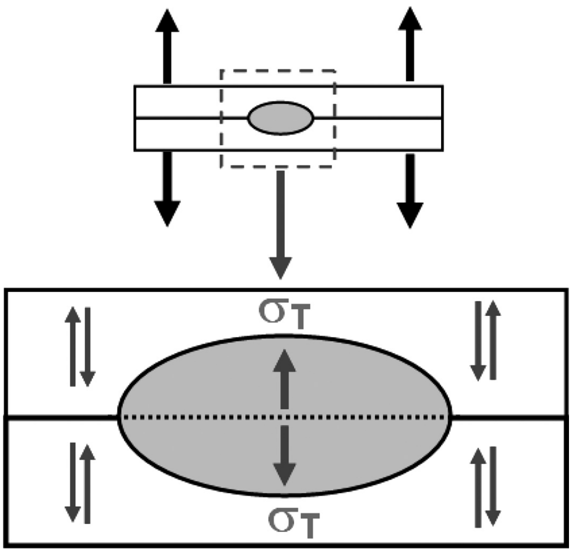

Figure 5: Simple model describing stress distribution in a spot weld during cross-tension test

Slika 5: Preprost model, ki prikazuje razporeditev napetosti v točkastem zvaru med prečnim nateznim preizkusom

One of the most probable defects during the resistance spot welding of the AHSSs is a shrinkage void[5,19,24,25] (**Figure 3a**). In the IF mode, the presence of voids decreases the effective FZ size and the load-bearing surface area, thus, decreasing the spot-weld failure strength. It is interesting to note that the AHSSs are highly prone to the shrinkage-void formation. This fact has been recognized as one of the main reasons for the high susceptibility of the AHSSs to the interfacial failure mode.[5,19] Therefore, the void level of RSWs should be taken into account when modeling the failure load in the interfacial failure mode. Here, similar to Sun et al.[26], modeling the failure load of an aluminium spot weld during a cross-tension test, the void factor (V) can be defined as follows:

$$V = \frac{A_{\text{total}} - A_{\text{Void}}}{A_{\text{total}}} \quad (6)$$

where A_{total} is the total area of the fusion zone on the faying interface and A_{void} is the projected area of the void in the fusion zone on the faying interface of the weld. Therefore, Equation (5) can be adjusted as follows:

$$F_{\text{IF}} = V\frac{\pi D^2}{4}\sigma_{\text{FZ}} \quad (7)$$

For the pull-out failure mode, it is assumed that a failure occurs when the shear stress at the circumference of one half of the cylindrical nugget reaches the ultimate shear strength of the softened HAZ (experimental investigations showed that the pull-out failure mode in the cross-tension test is initiated in the HAZ.)[27,28] Therefore, Equation (8) is suggested for the pull-out failure load in the cross-tension test, $(P_{\text{PF}})_{\text{CT}}$:

$$F_{\text{PF}} = \pi(D + 2X_{\text{HAZ}})\cdot t\cdot\tau_{\text{SCHAZ}} \quad (8)$$

where τ_{SCHAZ} is the ultimate shear strength of the pullout failure location (i.e., the sub-critical HAZ) and X_{HAZ} is the distance of the pullout-failure location from the fusion boundary. At the critical weld-nugget size, D_{C}, Equations (5) and (8) are equal. Therefore, D_{C} can be calculated using Equation (9):

$$(D_{\text{C}})_{\text{CT}} = \frac{2t\cdot\tau_{\text{SCHAZ}}}{V\sigma_{\text{FZ}}}\left[1+\left(1+\frac{2VX_{\text{HAZ}}}{t}\cdot\frac{\sigma_{\text{FZ}}}{\tau_{\text{SCHAZ}}}\right)^{0.5}\right] \quad (9)$$

The spot welds with $D < D_{\text{C}}$ tend to fail via the interfacial mode, unlike the welds with $D > D_{\text{C}}$ that tend to fail via the preferred pull-out 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 a material's tensile strength and its hardness. Also, the shear strength of a material can be linearly related to its tensile strength with the constant coefficient, f. Therefore, Equation (9) can be rewritten as follows:

$$(D_{\text{C}})_{\text{CT}} = \frac{2t\cdot f}{VK}\left[1+\left(1+\frac{2VKX_{\text{HAZ}}}{ft}\right)^{0.5}\right] \quad (10)$$

where K is the hardness ratio of the FZ to the sub-critical HAZ ($H_{\text{FZ}}/H_{\text{SCHAZ}}$).

3.1.4 Critical FZ during the TS loading

In previous work,[29] in the light of the failure mechanism, using a simple stress analysis, an analytical mode was proposed to predict the failure mode of spot welds during the tensile-shear test. $(D_{\text{C}})_{\text{TS}}$ was correlated to the hardness characteristics and void factor as follows:

$$(D_{\text{C}})_{\text{TS}} = \frac{2t}{fVK}\left[1+\left(1+\frac{2VfKX_{\text{HAZ}}}{t}\right)^{0.5}\right] \quad (11)$$

where t is the sheet thickness, K is the hardness ratio of the FZ to the sub-critical HAZ ($H_{\text{FZ}}/H_{\text{SCHAZ}}$), V is the void factor, X_{HAZ} is the HAZ width and f is the ratio of the shear strength to the tensile strength of the metal.

3.2 Model validation

According to the proposed models, the hardness characteristics play the key role in determining the failure mode of resistance spot welds. Rapid heating and cool-

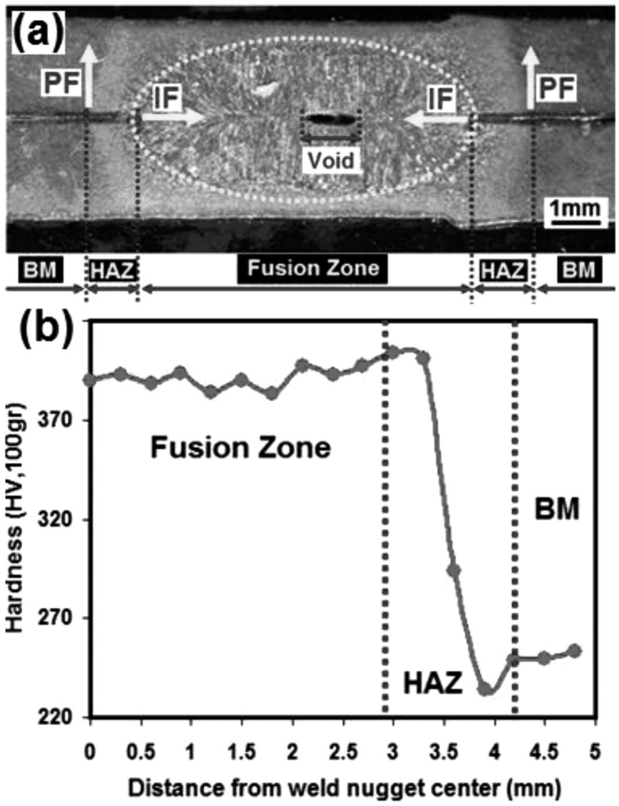

Figure 6: a) Typical macrostructure along the two main failure paths during cross-tension test and b) typical hardness profile of DP780 resistance spot welds

Slika 6: a) Značilna mikrostruktura vzdolž obeh poti preloma pri prečnem nateznem preizkusu in b) značilen potek trdote v uporovnem točkastem zvaru DP780 ing induced by the resistance-spot-welding thermal cycles significantly alter the microstructure in the joint zone. A typical macrostructure of DP780 spot welds is shown in **Figure 6a** indicating three distinct zones, namely, the fusion zone (FZ), the heat-affected zone (HAZ) and the base metal (BM). **Figure 6b** shows a typical hardness profile of the DP780 welds. The hardness profile exhibits three important phenomena:

(i) A hardening of the FZ: The average hardness of the FZ is 380 HV which is higher compared to the base-metal hardness (i.e., 230 HV). The high hardness of the FZ can be attributed to the martensite formation in the FZ.

(ii) A hardening in the HAZ: In the upper critical heat-affected zone (UCHAZ) where the peak temperatures are above A_{c1} during the welding, the base-metal microstructure transforms into austenite. On the subsequent cooling, austenite transforms into martensite. Therefore, in the UCHAZ, the local post-weld martensite content can be above the level of the as-manufactured steel, leading to a higher local hardness.[30]

(iii) A softening in the HAZ: The sub-critical heat-affected zone (SCHAZ) where the peak temperatures are below A_{c1} exhibits a reduction in the hardness (softening) with respect to the BM. It is reported that the location of the minimum hardness in a softened HAZ corresponds to A_{c1}. It is well documented that this phenomena is due to the tempering with the pre-existing martensite in the sub-critical HAZ.[5,30]

According to the hardness profile, the average hardness values of the FZ and SCHAZ are 380 HV and 230 HV. The hardness ratio is calculated as 1.65. The void factor (V) of the spot welds failed in the IF mode was determined using their fracture-surface macrograph. The average void factor of all the samples failed in the IF mode for the investigated DP780 spot welds is about 0.9 (i.e., 20 % of the area of the weld centerline plan exhibits a void). The average width of the HAZ (X_{HAZ}) is around 1 mm. The ratio of the shear strength to the tensile strength (f) is reported as 0.7–0.8. Here, an average value of 0.75 is considered. Now, the critical fusion zone (D_C) can be estimated for both TS and CT loading conditions using Equations (10) and (11):

(i) The critical fusion zone in the TS loading: According to Equation (10) the calculated D_C is 6.1 mm. As can be seen in **Figure 4**, at the welding current lower than 9 kA, the FZ size is lower than D_C and, consequently, the welds fail in the IF mode. On the other hand, the welds made at the welding current equal or higher than 9 kA exhibit a FZ that is higher than D_C and, hence, they fail in the PF mode. Indeed, the transition of the failure mode from the IF to the PF is well predicted using the proposed procedure.

(ii) The critical fusion zone in the CT loading: According to Equation (9), the calculated $(D_C)_{TS}$ is 9.7 mm. According to **Figure 4**, all the spot welds made in this study had the FZ size lower than 9.7 mm. Therefore, it is not surprising that all the spot welds failed in the IF mode during the TS loading.

4 CONCLUSIONS

The failure-mode transition for the resistance spot-welded DP780 advanced high-strength steel during the tensile-shear loading and cross-tension loading is studied. The following conclusions can be drawn from this work:

1. The industrial weld-nugget sizing criterion of $4t^{0.5}$ is not sufficient to ensure the pullout failure mode during the cross-tension and tensile-shear testing of DP780 resistance spot welds.
2. Accoding to the theoretical analysis presented in this study the failure-mode transition of the DP780 spot welds in the cross-tension loading condition is governed by the sheet thickness, the FZ hardness, the sub-critical HAZ hardness, the shrinkage voids and the width of the HAZ.
3. The following relation is proposed to predict the minimum FZ size (D_C) required to ensure the pull-out failure mode during the cross-tension test of the DP780 spot welds:

$$(D_C)_{CT} = \frac{2t \cdot f}{PK}\left[1+\left(1+\frac{2VKX_{HAZ}}{ft}\right)^{0.5}\right]$$

where t is the sheet thickness, K is the hardness ratio of the FZ to the sub-critical HAZ (H_{FZ}/H_{SCHAZ}), V is the void factor, X_{HAZ} is the HAZ width and f is the ratio of the shear strength to the tensile strength of the metal. The proposed analytical model successfully predicts the critical FZ size for the DP780 spot welds.

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