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FAILURE-MODE TRANSITION IN RESISTANCE SPOT WELDED DP780 ADVANCED HIGH-STRENGTH STEEL: EFFECT OF LOADING CONDITIONS

PREHOD VRSTE PRELOMA UPOROVNO TOČKASTO VARJENEGA NAPREDNEGA VISOKOTRDNOSTNEGA JEKLA DP780: VPLIV RAZMER PRI OBREMENJEVANJU

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Resistance spot welds of advanced high-strength steels (AHSSs) exhibit a high tendency to fail in the interfacial failure mode (i.e., a failure through the fusion zone). It is also evident that the conventional recommendations (based on the sheet thickness) for weld sizing, ensuring the pullout failure mode of welds, are not dominant in AHSS welds. Therefore, there is a need to study the failure mode of advanced high-strength-steel spot welds. This paper aims at investigating the transition from the interfacial to the pullout failure mode during various loading conditions including the tensile-shear test, cross-tension and coach-peel tests of DP780 spot welds. It was found that there is a critical fusion-zone (FZ) size ensuring the pullout failure mode in each loading condition. The results showed that the critical fusion size increased in the following order: cross-tension, coach-peel and tensile-shear test. The behaviour of the transition from the interfacial to the pullout failure mode was explained in terms of the stress state of the weld for each loading mode.

Keywords: resistance spot welding, failure mode, DP780, loading condition

Uporovni točkasti zvari naprednega visokotrdnostnega jekla (AHSS) izkazujejo nagnjenje k porušitvi med ploskvama (porušitev skozi področje zvara). Razvidno je tudi, da pri AHSS-zvarih ne veljajo navadna priporočila (glede na debelino pločevine) za velikost zvara, ki bi omogočila porušitev z iztrganjem zvara. Zato je bilo treba preučiti način porušenja točkastih zvarov pri naprednih visokotrdnostnih jeklih. Namen tega članka je opis preiskave načina porušitve od porušitve med ploskvama do porušitve z iztrganjem pri različnih obremenitvah, vključno z natezno-strižnim preizkusom točkastih zvarov DP780. Ugotovljeno je bilo, da obstaja kritična velikost FZ, ki omogoča, da se zagotovi porušitev z izpuljenjem pri vseh obremenitvah. Rezultati so pokazali, da velikost zvara narašča v naslednjem vrstnem redu: prečni natezni preizkus, natezni preizkus spojenih kotnikov (coach-peel) in natezno-strižni preizkus. Za vsako vrsto obremenitve je razložen z napetostmi prehoda iz medploskovne porušitve v porušitev z izpuljenjem.

Ključne besede: uporovno točkasto varjenje, način porušitve, DP780, način obremenitve

1 INTRODUCTION

Vehicle crashworthiness, 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 mechanical performance of spot welds. Therefore, an evaluation of the spot-weld quality is a vital issue for the reliability of the vehicle and for improving the economics of the vehicle production.[1–6]

The failure mode is the manner in which a spot weld fails. Generally, the resistance spot weld (RSW) failure occurs in two modes: the interfacial failure (IF) and the pullout failure (PF).[4–6] In the interfacial mode, a failure occurs via a crack propagation, while, in the pullout mode, a failure occurs via a nugget withdrawal from one sheet. Generally, the pullout mode is the preferred failure mode due to its higher associated plastic deformation and energy absorption. Thus, vehicle crashworthiness, as the main concern in the automotive design, is dramatically reduced if spot welds fail via the interfacial mode.[7–10] The tortuosity of the crack path in the pullout mode dissipates more energy in crash conditions and is preferable to the interfacial failure mode which does little to deflect the direction of crack propagation.[11] Therefore, it is necessary to adjust the welding parameters so that the pullout failure mode is guaranteed.

The failure mode and the failure mechanism largely depend on the complex interplay between the weld geometry and the material properties of the fusion zone (FZ)/heat-affected zone (HAZ)/base metal (BM) as well as between the test geometry and the stress state of each weld.[12,13] Therefore, the prediction of the failure mode and failure location is a challenging issue.

Spot welds in the real-service conditions experience complex loading conditions including shear, tensile, compression, bending and torsion stresses. This paper aims at investigating the failure-mode transition from the interfacial failure mode to the pullout mode under the tensile-shear (TS), cross-tension (CT) and coach-peel (CP) loading conditions.

2 EXPERIMENTAL PROCEDURE

DP780 dual-phase steel sheets 2 mm thick were used as the base metals. The chemical composition of the investigated steel is Fe-0.16C-0.24Si-0.67Mn-0.04Cr-0.01Mo (mass fractions, %). The values of the ensile strength and the elongation of the base metal are 820 MPa and 14 %, respectively. Resistance spot welding was performed using a 120 kV A AC pedestal-type resistance-spot-welding machine, controlled by a PLC operating at 50 Hz. Welding was conducted using a 45° truncated cone RWMA Class 2 electrode with an face diameter 8 mm.

To study the effects of the welding conditions on the weld performance, several welding schedules were used. The electrode force and holding time were selected on the basis of the thickness of the base material and were 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 time of 0.5 s. The welding parameters were chosen below the expulsion limit to avoid an undesirable failure mode. Ten samples were prepared for each welding condition including three samples for the tensile-shear test, three samples for the cross-tension test, three samples for the coach-peel test and one sample for the metallographic investigation and measurement of the weld size.

The samples for the mechanical testing were prepared according to the AWS standard.[14] The mechanical tests were performed at a cross-head speed 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.

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

3 RESULTS AND DISCUSSION

3.1 Microstructure-hardness characteristics

A typical macrostructure of a joint is shown in **Figure 1a** indicating three distinct zones, namely, the fusion zone (FZ), the heat-affected zone (HAZ) and the base metal (BM). A hardness profile of a joint is shown in **Figure 1b**. The hardness of the BM is averaged at 250 HV which corresponds to its ferritic martensitic microstructure (**Figure 1c**). A high hardness of the FZ can be related to the martensite formation (**Figure 1d**). The martensite formation in the FZ is attributed to the high cooling rate of the resistance-spot-welding process due to the presence of the water-cooled copper electrodes and their quenching effect as well as the short welding cycle. It was shown with the modeling that the spot welds with the thicknesses of up to 2 mm typically solidify in fewer than 3–4 cycles.[15] Gould et al.[16] developed a simple analytical model predicting the cooling rates of the resistance spot welds. According to this

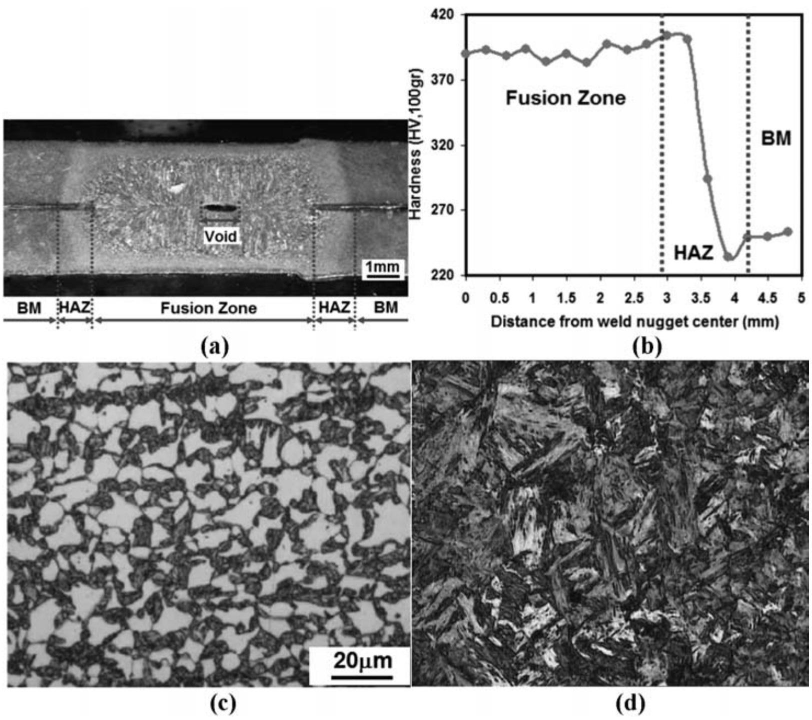

Figure 1: Typical: a) macrostructure, b) hardness profile of the resistance spot welds made on DP780, c) BM microstructure, d) FZ microstructure

Slika 1: Značilna: a) mikrostruktura, b) profil trdote uporovnega točkastega zvara na DP780, c) BM-mikrostruktura, d) FZ-mikrostruktura model, the cooling rate for the thickness 2 mm is about 3000 K s^{-1}. For steels, the critical cooling rate required for a formation of the martensite in the microstructure can be estimated using the following equation:[17]

$$\lg v = 7.42 - 3.13\,w(\mathrm{C}) - 0.71\,w(\mathrm{Mn}) - 0.37\,w(\mathrm{Ni}) - 0.34\,w(\mathrm{Cr}) - 0.45\,w(\mathrm{Mo}) \quad (1)$$

where v is the critical cooling rate in K h^{-1}. The calculated critical cooling rate for the investigated steels is about 740 K s^{-1}. Since the experienced cooling rate in the FZ is higher than the critical cooling rates needed for a martensite formation, it is not surprising that a martensite structure is present in the FZ.

A reduction in the hardness (softening) with respect to the BM was observed in the sub-critical HAZ of the DP780 spot welds. The minimum hardness of the HAZ is about 235 HV (i.e., the maximum hardness reduction of 15 HV). The occurrence of the HAZ softening during the RSW of dual-phase steel is well documented in the literature.[6,18–21]. This is related to the martensite tempering.

3.2 Failure-mode-transition behavior

All the DP780 spot welds failed in the interfacial mode in the TS loading condition. However, during the CT and CP tests, apart from the interfacial failure mode, the pullout mode was also observed. **Figure 2** shows typical fracture surfaces of the spot welds that failed in the interfacial mode and the pullout mode during the CT test.

The FZ size is one of the key factors in controlling the failure mode of spot welds. **Figure 3** shows the correlation among the welding current, the FZ size and the failure mode of the spot welds during the TS, CT and CP loading conditions. It is well documented that there is a critical FZ, above which the pullout failure mode is guaranteed.[4–6,11–13] The critical FZ (D_C) ensuring the pullout failure mode was determined by examining the weld-fracture surfaces. The critical FZ size (defined as the FZ size between the maximum weld size leading to the IF mode and the minimum weld size leading to the PF mode) was identified in **Figure 3**. In the CT test, the spot welds with the fusion-zone sizes larger than 7.1 mm

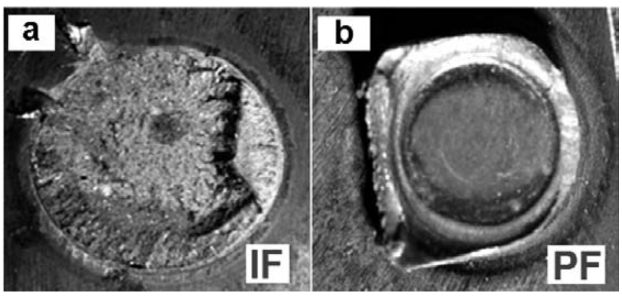

Figure 2: Typical fracture surface during the cross-tension tests: a) interfacial failure (IF) and b) pullout failure (PF)

Slika 2: Značilna površina preloma pri prečnem nateznem preizkusu: a) porušitev med ploskvama (IF) in b) porušitev z iztrganjem (PF)

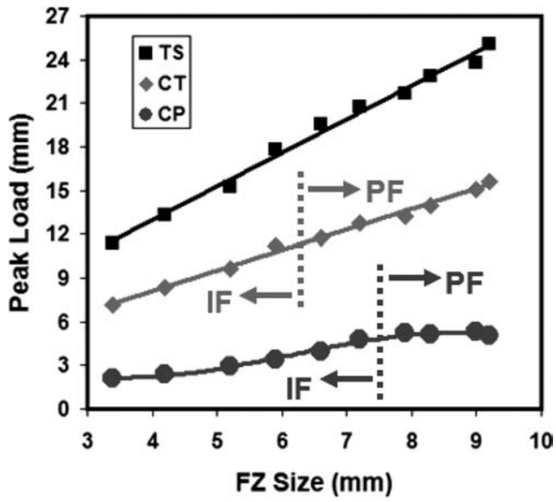

Figure 3: Effect of the fusion-zone (FZ) size on the peak load and failure mode of the spot welds during the tensile-shear (TS), coach-peel (CP) and cross-tension (CT) tests. Note that all the spot welds failed in the interfacial mode during the TS test.

Slika 3: Vpliv velikosti zvara (FZ) na konico obremenitve in način porušitve točkastih zvarov med natezno-strižnim (TS) preizkusom, preizkusom coach-peel (CP) in prečnim nateznim preizkusom (CT). Vsi zvari so se porušili med ploskvama pri natezno-strižnem TS-preizkusu.

failed in the pullout failure mode, while, during the CP test, the spot welds with the fusion-zone sizes larger than 7.9 mm failed in the pullout failure mode. All the spot welds exhibit the interfacial failure mode during the tensile-shear test. Therefore, the tendency to fail in the interfacial failure mode is increased in the following order: CT, CP and TS loading conditions. To explain the IF to PF transition behaviour, first, the stress state in these loading conditions should be briefly described. Simple models describing the stress distribution at the interface and circumference of a weld nugget during the TS,[12] CP[10] and CT tests are shown in **Figure 4**. The following points can be drawn from this figure:

(1) During the TS tests, the shear stresses are dominant at the interface. As can be seen in **Figure 4**, one leg of the lower sheet and one leg of the upper sheet are subjected to the tensile stress. In the IF mode, the shear stress at the sheet/sheet interface is the driving force of the failure. The tensile stress at the nugget circumference is the driving force for the PF mode.

(2) During the CP tests, in the IF mode, the tensile stress at the sheet/sheet interface is the driving force of the failure. The bending stress is the driving force for the PF mode during the CP test.

(3) During the CT test the notch at the sheet/sheet interface experiences the tensile stress (i.e., the opening mode, mode I of the loading condition). According to **Figure 4**, the shear stress at the nugget circumference (i.e., the HAZ) is the driving force for the PF mode during the CT test.

To explain the IF to PF transition behaviour, the following points should be considered:

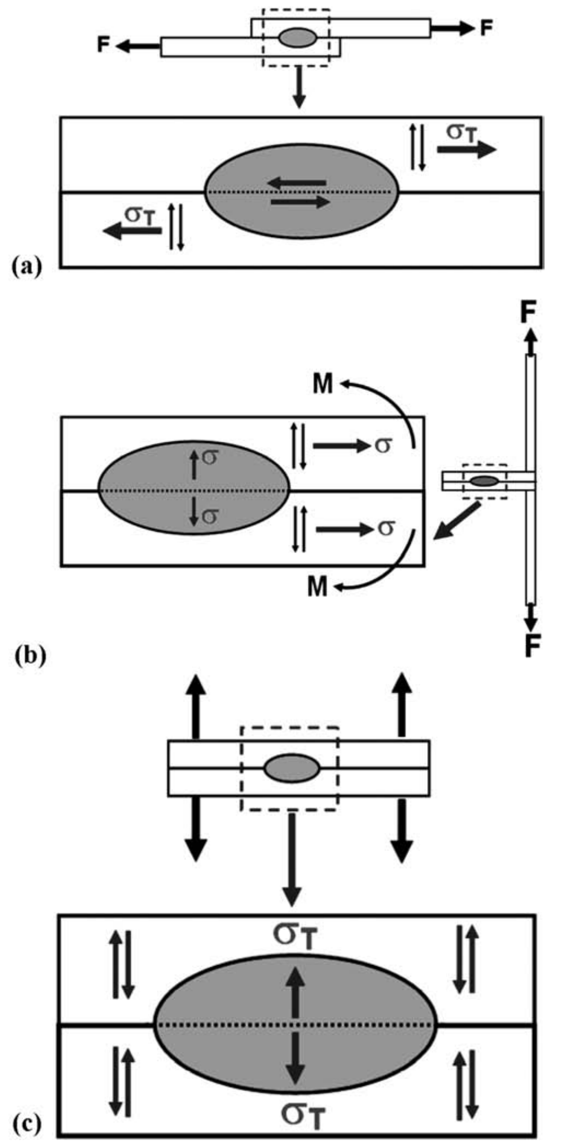

Figure 4: Simple models describing the stress distribution at the interface and circumference of a weld nugget during the: a) tensile-shear, b) coach-peel and c) cross-tension tests

Slika 4: Enostavni modeli, ki opisujejo razporeditev napetosti na stiku in okrog jedra zvara med: a) natezno-strižnim preizkusom, b) preizkusom coach-peel in c) nateznim prečnim preizkusom

(i) In the TS, the driving force for the IF mode is the shear stress at the sheet/sheet interface, while in the CT and CP tests, the tensile stress at the sheet/sheet interface is the driving force. It is well known that the shear strength of the metals is lower than their tensile strength. This point can partly explain the higher tendency of the TS samples to fail in the IF mode.

(ii) The driving force for the PF mode in the CT test is the shear stress at the nugget circumference, while in the TS and CP tests, the tensile stress is the driving force. Again, the fact that the shear strength of the metals is lower than the tensile strength can partly explain the higher tendency of the CT samples to fail in the pullout mode. Moreover, Radakovic and Tumuluru[22] showed, with the finite-element modeling, that the location of the maximum stress is in the HAZ. This factor coupled with the softening in the HAZ of DP780 results in the strain localization in the weld circumference enhancing the pullout failure mode.

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 the weld-nugget sizing. Various industrial standards recommend the minimum weld size for a given sheet thickness:

(I) AWS/ANSI/AISI,[14] a weld-button sizing, ensuring that the weld size is large enough for carrying the desired load, is expressed with equation (2):

$$D = 4t^{0.5} \tag{2}$$

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

(II) According to the Japanese JIS Z3140[23] and the German DVS2923[24] standards, the required weld size is specified according to equation (3):

$$D = 5t^{0.5} \tag{3}$$

Table 1 compares the experimentally determined critical FZ size for the spot welds made on DP780 steel 2 mm that failed under various loading conditions and the weld size determined by industrial recommendations. As can be seen, the most common weld-sizing criterion of $4t^{0.5}$ is not sufficient for producing a weld in the PF mode in all the loading conditions. Despite the fact that the sizing based on the $5t^{0.5}$ rule is sufficient for producing the PF mode during the CT test, it is not sufficient to avoid the interfacial failure during the TS and CP tests. 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. Despite the fact that the industrial recommendation works 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. Therefore, it seems that in addition to the sheet thickness, the metallurgical factors should be considered to precisely analyze and predict the RSW failure mode.

Table 1: Critical fusion-zone size required to ensure the pullout failure mode during the cross-tension (CT), coach-peel (CP) and tensile-shear (TS) tests along with the common industrial recommendations for spot-weld sizing

Tabela 1: Kritična velikost zvara, ki zagotavlja porušitev z izpuljenjem med prečnim nateznim preizkusom (CT), preizkusom coach-peel (CP) in natezno-strižnim (TS) preizkusom, skupaj s splošnim industrijskim priporočilom za velikost točkastega zvara

$(D_C)_{CT}$	$(D_C)_{CP}$	$(D_C)_{TS}$	$4t^{0.5}$	$5t^{0.5}$
6.6 mm	7.9 mm	N. D*	5.6 mm	7.1 mm

* N. D: Not determined – all the spot welds failed in the TS loading condition

4 CONCLUSIONS

The failure modes of the resistance spot welds made on DP780 dual-phase steels 2 mm thick were investigated under the tensile-shear, coach-peel and cross-tension tests. It was observed that the tendency to fail in the interfacial mode is the highest in the tensile-shear loading condition, while the cross-tension test exhibits a higher tendency to fail in the pullout failure mode. This was explained in terms of the stress state at the weld interface and nugget circumference during each loading mode. During the cross-tension test, a high-stress HAZ coupled with the presence of softening in the HAZ of DP780 results in the strain localization in the weld circumference enhancing the pullout-failure mode. It is shown that the industrial weld-nugget-sizing recommendation of $4t^{0.5}$ was not sufficient for producing the welds with the pullout failure mode during the mechanical testing of the DP980 resistance spot welds.

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