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DEPENDENCE OF THE FRACTURE MODE ON THE WELDING VARIABLES IN THE RESISTANCE SPOT WELDING OF FERRITE-MARTENSITE DP980 ADVANCED HIGH-STRENGTH STEEL

ODVISNOST NARAVE PRELOMA OD SPREMENLJIVK VARJENJA PRI UPOROVNEM TOČKASTEM VARJENJU NAPREDNEGA FERITNO-MARTENZITNEGA VISOKO TRDNOSTNEGA JEKLA DP980

Majid Pouranvari[1], Eslam Ranjbarnoodeh[2]

[1]Materials and Metallurgical Engineering Department, Dezful Branch, Islamic Azad University, Dezful, Iran
[2]Young Researchers Club, East Tehran Branch, Islamic Azad University, Tehran, Iran
mpouranvari@yahoo.com

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Failure mode is a qualitative measure of the performance of a resistance spot weld. To ensure the reliability of resistance spot welds during a vehicle's lifetime, the process parameters should be adjusted so that the pullout failure mode is guaranteed. Dual-phase steel resistance spot welds are prone to interfacial failure mode. In this paper the effects of welding parameters, including the welding current, the welding time and the electrode force, on the failure mode of DP980 resistance spot welds are investigated. The process window to obtain the desired pullout failure mode was determined. It was shown that increasing the electrode force increases the minimum welding current and the welding time required to obtain the PF mode.

Keywords: resistance spot welding, DP980, failure mode, welding parameters

Narava preloma je kvalitativno merilo zmogljivosti točkastega zvara. Za zagotavljanje zdržljivosti točkastih zvarov med obratovanjem vozila je treba parametre procesa prilagoditi tako, da je zagotovljena porušitev z iztrganjem. Točkasti zvari pri dupleksnih jeklih so nagnjeni k porušitvi med ploskvami. V tem članku so bili preiskovani učinki parametrov pri varjenju, vključno z varilnim tokom, časom varjenja in pritiskom elektrode, na značilnost preloma v uporovnih zvarih DP980. Določeno je bilo procesno okno za doseganje želene porušitve z iztrganjem. Izkazalo se je, da povečanje pritiska elektrode poveča minimalni tok in čas varjenja, ki sta potrebna za zagotavljanje porušitve z izpuljenjem (PF).

Ključne besede: uporovno točkasto varjenje, DP980, vrsta preloma, parametri pri varjenju

1 INTRODUCTION

There is an increasing demand for high-strength steel sheets in the automotive industry, in order to improve fuel efficiency, the occupants' safety and reduce the weight of the auto body. Due to the combination of excellent strength and formability, advanced high-strength steels (AHSS) offer the potential for improvement in vehicle-crash performance without the addition of any excess weight. Dual-phase (DP) steel is one of the most common AHSS steels. DP steels exhibit a composite microstructure of martensite and ferrite[1,2]. As a result of the development and commercialization of new DP steels for applications in automotive bodies, there is a need to study the spot welding behavior of these materials.

According to the literature, problems associated with the resistance spot welding of DP steels can be summarized as follows[1–12]:

(i) High susceptibility to failure in interfacial failure mode
(ii) High susceptibility to expulsion
(iii) Sensitivity to the formation of shrinkage voids
(iv) High hardness of the fusion zone due to martensite formation, which can have an adverse effect on the failure mode during some loading conditions (e.g., peel test)

The failure mode of resistance spot welds (RSWs) is a qualitative measure of the joint quality. Basically, spot welds can fail in two distinct modes[3,4]:

(i) Interfacial failure (IF), in which failure occurs via crack propagation through the fusion zone.
(ii) Pullout failure (PF), in which failure occurs via the complete withdrawal of a weld nugget from one sheet.

Failure mode can significantly affect the load-bearing capacity and energy-absorption capability of RSWs. Generally, the pullout mode is the preferred failure mode due its higher associated plastic deformation and energy absorption[5]. Thus, vehicle crashworthiness, as the main concern in automotive design, can dramatically reduce if a spot weld fails via the interfacial mode. The pullout failure mode during quality control indeed indicates that the weld would be able to transmit a high level of force. This will cause severe plastic deformation in its adjacent components, and increases the strain-energy dissipation under crash conditions[6]. Therefore, it is necessary to adjust the welding parameters so that the pullout failure mode is guaranteed.

Failure of the resistance spot welds is a complicated phenomenon. The failure mode and the failure mechanism are largely dependent upon the complex interplay between the weld geometry, the materials properties, the test geometry, and the stress state in each weld[7,8].

A RSW of AHSS exhibits a greater tendency to fail in the interfacial failure mode than traditional steels (i.e., low-carbon and HSLA steels)[9,10]. For low-carbon steel, destructive testing usually results in the pullout failure mode. However, it has been observed that AHSS spot welds also fail in several other non-traditional modes. In order to understand the effect of various failure modes on the mechanical performance of the joint; first, the potential failure modes should be characterized.

Considering the development and commercialization of new DP steels for application in automotive bodies, there is an increasing need to study the spot-welding behavior of these materials. Considerable efforts are focused on the spot-welding behavior of DP600 [9–12], but there are only limited published works regarding the weldability of higher grades of dual-phase steels such DP980. In this paper, the effects of the welding parameters on the failure mode of DP980 resistance spot welds under tensile-shear testing are investigated.

2 EXPERIMENTAL PROCEDURE

1.5-mm-thick DP980 dual-phase steel was chosen for this study. The chemical composition of the steel is given in **Table 1**. The spot welding was performed using a 120 kVA AC pedestal-type resistance spot-welding machine operating at 50 Hz, controlled by a programmable logic controller (PLC). The welding was conducted using a 45-degree truncated-cone RWMA Class-2 electrode with an 8 mm face diameter. To study the effects of the weld FZ size on the failure mode, spot welding was performed in 72 different welding conditions. The welding conditions are given in **Table 2**. The holding time and the squeeze time were selected based on the sheet thickness. The welding current, welding time and electrode force were systematically changed to explore the effect of the welding parameters on the weld quality.

The samples for the metallographic examinations were prepared using a standard metallographic procedure. The weld microstructures and macrostructures were examined with optical microscopy. The weld nugget (fusion zone) sizes were measured on the weld cross-section parallel to the rolling direction. A 4 % Nital etching reagent was used to reveal the fusion-line boundary. The quasi-static tensile-shear test samples were prepared according to the ANSI/AWS/SAE/D8.9-97 standard[13]. The 140 mm × 60 mm samples were sheared and a single spot weld was made at the center of an overlapped area that measured 45 mm. The tensile-shear tests were performed at a cross-head speed of 2 mm/min with an Instron universal testing machine. The failure mode was determined by observing the weld-fracture surfaces. Using the metallographic data and post-mechanical-testing observations, the correlation between the welding parameters, the fusion-zone size and the failure mode was determined.

A Vickers microhardness test was used to determine the hardness profile parallel to the sheets interface (20 μm away from the weld centerline), using a Bohler microhardness tester. An applied load of 100 g and a time of 20 s were used. The hardness indentations were spaced 0.25 mm apart.

Table 1: Chemical composition of the DP980 used in this study, in mass fractions, *w*/%

Tabela 1: Kemijska sestava DP980, uporabljenega v študiji, v masnih deležih *w*/%

C	Mn	Si	Cr	Mo
0.14	1.7	0.08	0.25	0.16

Table 2: Welding conditions

Tabela 2: Pogoji pri varjenju

Welding Current (kA)	7-8-9-10-11-12
Welding Time (s)	0.2-0.3-0.4-0.5
Electrode Force (kN)	4-4.5-5
Holding Time (s)	0.2
Squeeze Time (s)	0.4

3 RESULTS

Figure 1 shows the macrostructure of the DP980 resistance spot weld indicating that there are three distinct microstructural zones:

(i) Weld nugget (WN) or fusion zone (FZ), which is melted during the welding process and is re-solidified showing a cast structure. The macrostructure of the weld nugget consists of columnar grains.

(ii) Heat-affected zone (HAZ), which is not melted but undergoes microstructural changes.

(iii) Base metal (BM)

Figure 2 shows a typical hardness profile of the spot welds. The average hardness of the fusion zone is about 475 HV, which higher than that of the BM (i.e., 300 HV).

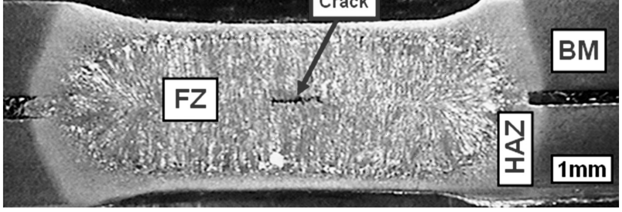

Figure 1: A typical macrostructure of DP980 RSW

Slika 1: Značilna makrostruktura uporovnega točkastega zvara DP980

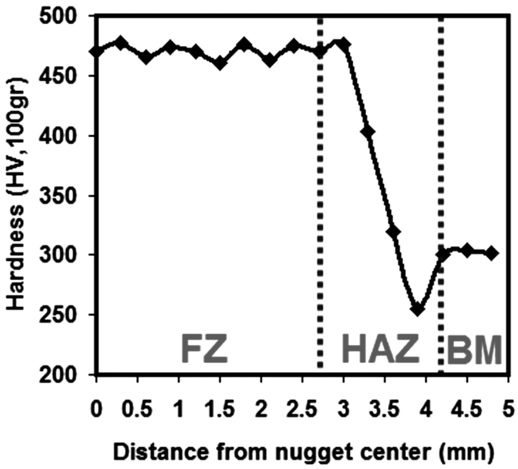

Figure 2: A typical hardness profile for DP980 spot welds
Slika 2: Značilen profil trdote v točkastem zvaru DP980

According to the hardness profile of the joint, the HAZ exhibits both hardening and softening phenomena. Generally, the HAZ can be divided into two parts: the supper-critical heat-affected zone where the peak temperatures are above A_{c1} during the welding, and the sub-critical heat-affected zone where the peak temperatures are blow A_{c1}. Hardening in comparison to the base metal was observed in the supper-critical HAZ. A reduction in the hardness (softening) with respect to the BM was observed in the sub-critical HAZ. The minimum hardness in the HAZ is about 250 HV (i.e., a maximum hardness reduction of 50 HV).

The FZ size, which is defined as the width of the weld nugget at the sheet/sheet interface in the longitudinal direction, is one of the most important factors in determining the quality of the spot welds[1,3–8]. Therefore, to understand the resistance spot weldability of DP980, it is necessary to study the relationship between the welding parameters and the fusion-zone size. The welding current, the welding time and the electrode force are the main controlling parameters for the FZ size.

Figure 3 shows the effect of the welding current and the welding time on the FZ size at three levels of electrode force. Based on these results, the following conclusions can be drawn:

(i) Welding current has a profound effect on the weld-nugget growth. Increasing the welding current increases the weld-nugget size.

(ii) Increasing welding time increases the weld-nugget size.

(iii) Increasing the electrode force decreases the weld-nugget size. Indeed, when applying the electrode force, there is need to use a higher welding current and a longer welding time to obtain a specific weld-nugget size.

Two distinct failure modes were observed during the static tensile-shear test: interfacial fracture and nugget pullout. Typical fracture surfaces of spot welds in the IF and PF modes are shown in **Figure 4**. The effect of the welding parameters (welding time and welding current at three levels of electrode force) on the failure mode of the DP980 spot welds is shown in **Figure 5**. The following conclusions can be drawn from this figure:

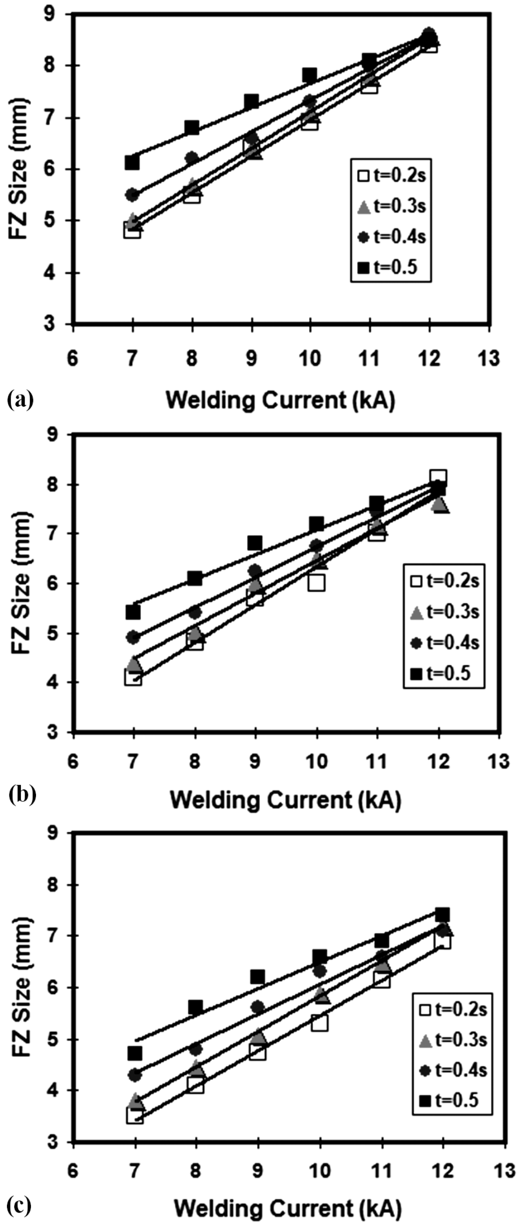

Figure 3: FZ versus welding time and welding current at electrode force of: a) 4 kN, b) 4.5 kN and c) 5 kN
Slika 3: Cona zlivanja (FZ) v odvisnosti od časa varjenja in toka pri varjenju pri pritisku elektrode: a) 4 kN, b) 4,5 kN in c) 5 kN

- At a constant welding time and electrode force, an increasing welding current leads to the transition of the failure mode from the interfacial to the pullout mode. For example, at an electrode force of 4 kN and using a welding time of 0.2 s, increasing the welding current beyond 10 kA leads to the transition of the failure mode from IF to PF. At an electrode force of 4 kA and using welding times of (0.2, 0.3, 0.4 and 0.5)

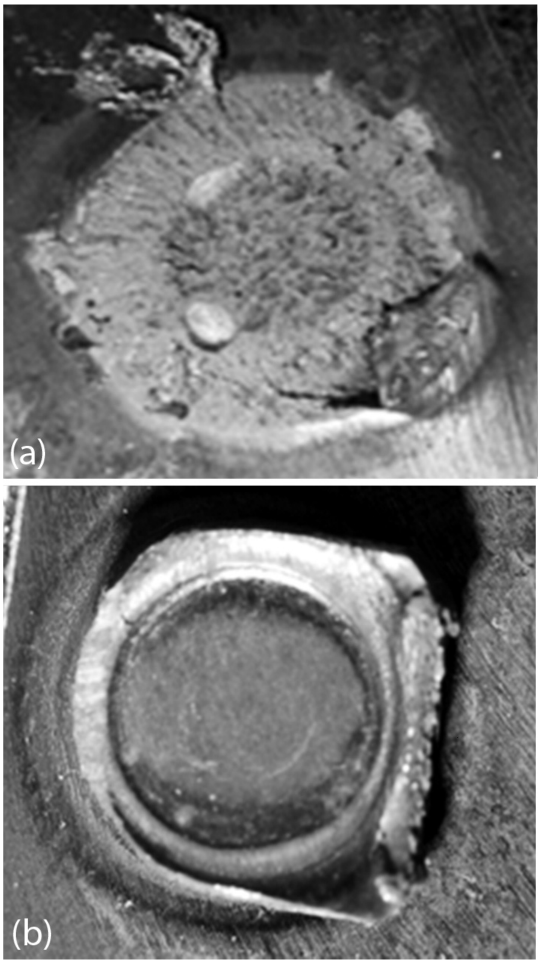

Figure 4: Typical fracture surface of failure mode: a) interfacial, b) pullout

Slika 4: Značilna površina preloma pri vrsti preloma: a) med ploskvami, b) izpuljenje

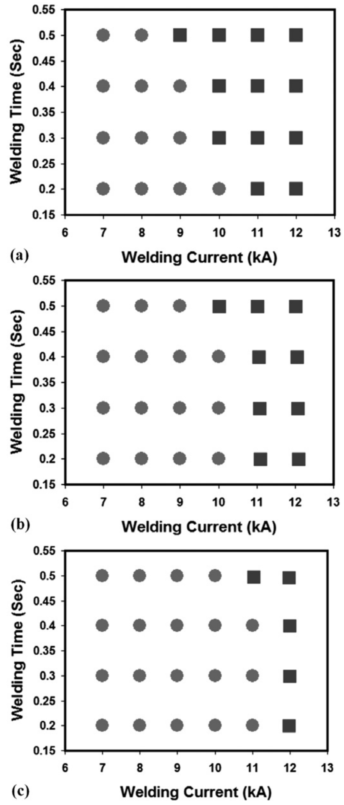

Figure 5: Effect of welding variables on the failure mode: a) electrode force 4 kN, b) electrode force 4.5 kN, c) electrode force 5 kN. Circles indicate IF mode and squares indicate PF mode.

Slika 5: Vpliv spremenljivk pri varjenju na vrsto preloma: a) pritisk elektrode 4 kN, b) pritisk elektrode 4,5 kN, c) pritisk elektrode 5 kN. Krogi označujejo prelom med ploskvami (IF), kvadrati pa prelom z izpuljenjem (PF).

s, the minimum welding currents required to ensure pullout mode are (11, 10, 10 and 9) kA, respectively. Welding using a current of lower than 9 kA leads to failure in the interfacial mode.

- Increasing the electrode force increases the minimum welding current required to obtain the PF mode. For example, in a welding time of 0.5 s and at an electrode force of 4 kN, a minimum welding current of 9 kA is required to obtain the PF mode. In the same welding time, as the electrode force is increased to 4.5 kN, a minimum welding current of 10 kA is required to avoid the interfacial failure mode. By increasing the electrode force to 5 kN, a minimum welding current of 11 kA is needed to obtain the pullout failure mode.

4 DISSCUSION

4.1 Analysis of hardness profile

The macro/microstructural attributes and hardness characteristics of the resistance spot welds are the most important factors affecting their failure behavior. The hardness variation across the joint can be analyzed in terms of the microstructure of the joint.

The higher hardness of the FZ compared to the hardness of the BM can be related to the formation of martensite in the FZ. Martensite formation in the FZ is attributed to the inherently high cooling rate of the resistance spot-welding process due to the presence of water-cooled copper electrodes and their quenching effect as well as the short welding cycle[3,14]. Gould et al.[14] developed a simple analytical model predicting the cooling rates of resistance spot welds. According to this model, the cooling rate for a sheet having a 1.5-mm thickness is about 4000 K s^{-1}. For steels, the required critical cooling rate to achieve a martensite phase in the microstructure can be estimated using the following equation[15]:

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

where V is the critical cooling rate in K h^{-1}.

The calculated critical cooling rate for DP980 steels is 115 K s^{-1}. The experimental cooling rates in the FZ are significantly higher than these values, so it is not surprising to find a martensite structure in the FZ.

Depending on the location and hence on the peak temperature reached, partial or full austenitization occurs within the super-critical HAZ. On subsequent cooling, austenite transforms to martensite. Therefore, in super-critical HAZ, the local post-weld martensite content could be above the level in the as-manufactured steel, leading to higher local hardness[16].

The occurrence of HAZ softening during the RSW of DP980 is well documented in the literature[1,5,14,16]. It is reported that the location of minimum hardness in the softened HAZ corresponds to A_{c1}. It is well documented that this phenomenon is due to the tempering of the pre-existing martensite in the sub-critical HAZ[16,17]. Recently, Baltazar et al.[16] studied the HAZ softening of DP980 RSW via a nano-indentation hardness test. They concluded that for the tempered region, the ferritic matrix presented a slight hardness reduction (probably due to the possible reduction in the dislocation density), while the tempered martensite seemed to have a major contribution to the measured softening on the micro-scale.

It is interesting to note that the effect of the welding parameters on the FZ hardness is not significant. Accordingly, due to the very high cooling rate of the RSW process, the effect of heat input on the final FZ microstructure can be ignored. Therefore, FZ hardness is not dependent on welding conditions. Despite the fact that FZ hardness does not vary significantly with the welding parameters, in the case of HAZ softening, the loss of hardness value in the HAZ becomes more severe as the heat input increases.

4.2 Effect of welding parameters on the FZ size

The amount of heat generated at the sheet-to-sheet interface during the spot-welding process is mainly responsible for nugget formation and its strength. The generated heat during resistance spot welding can be expressed as follows:

$$Q = R I_w^2 \, t_w \quad (2)$$

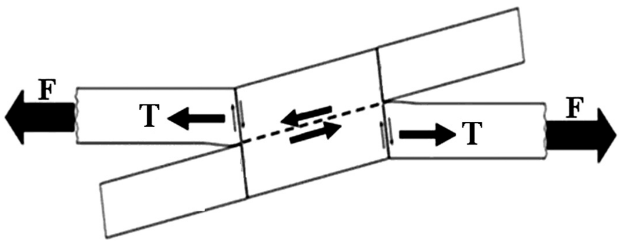

Figure 6: A simple model for stress distribution in resistance spot welds under tensile-shear test

Slika 6: Preprost model razporeditve napetosti v točkastem zvaru med natezno-strižnim preizkusom

where Q, R, I_w and t_w are the generated heat, the electrical resistance, the welding current and the welding time, respectively.

Therefore, the three main parameters affecting the weld nugget growth are the welding current, the welding time and the electrical resistance. This heat varies directly with the interface resistance, the weld time and the second power of the welding current. Again, this contact (interface) resistance varies in a complex manner and is influenced by the electrode force, the surface conditions of the sheets used and also with the geometry of the electrode tip. Increasing the welding current and the welding time increases the heat generation, which in turn causes an enlargement of the weld nugget.

The static electrical resistance (i.e., the contact resistance) is mainly governed by the electrode force, which in turn controls the weld-nugget formation[18]. In a ductile material, as a normal force is applied across the contact interface, the number of surface asperities supporting the applied load gradually increases due to their successive yielding. In other words, the true contact area will initially be a relatively small fraction of the macroscopic or apparent contact area. The true contact area will increase with the application of the load and, in the limit, will approach the apparent contact area[19]. Therefore, an increase in the electrode force decreases the electrical resistance and thus reduces the generated heat at the sheet/sheet interface.

4.3 Effect of fusion-zone size and welding parameters on the failure mode

To study the effect of FZ size on the failure mode, a box plot of failure mode versus FZ size was constructed (**Figure 7**). **Figure 7** indicates that there is a critical FZ size, above which the pullout failure mode is guaranteed. According to **Figure 7**, the minimum weld-nugget size required to ensure pullout failure mode is about 7 mm.

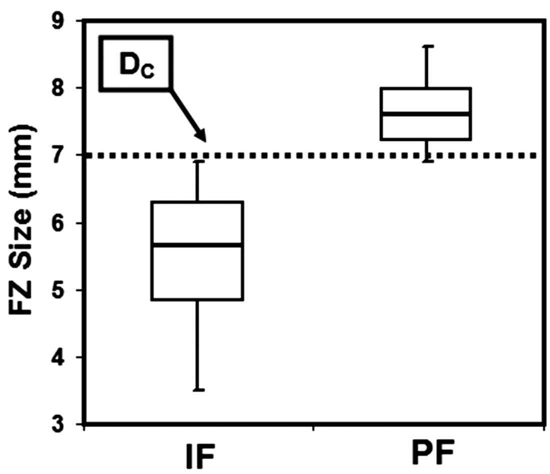

Figure 7: Box plot of FZ size versus failure mode

Slika 7: Prikaz velikosti področja zlivanja (FZ) in vrste preloma

The effect of FZ size on the failure mode can be explained in terms of the stress distribution in the spot weld during the tensile-shear test. **Figure 6** represents a simple stress analysis of the spot welds during the tensile-shear test. Failure is a competitive phenomenon, i.e., spot-weld failure occurs in a mode that needs less force. During the tensile-shear test, the shear stress at the sheet/sheet interface and the tensile stress created in the nugget circumference are the driving force for the interfacial and pullout failure modes, respectively. Each driving force has a critical value and the failure occurs in a mode in which the driving force reaches its critical value sooner. Physical weld attributes, particularly the weld-nugget size, are the most important governing parameters of the failure mode of resistance spot welds. The weld-nugget size affects the stress distribution around the spot welds during loading in the tensile-shear test. For those welds with a small weld size, the shear stress reaches its critical value before the tensile stress, causing failure in the circumference of the FZ (BM or HAZ). Therefore, failure tends to occur under the interfacial failure mode. Increasing the FZ size, increases the weld nugget resistance against interfacial (i.e., shear) failure. Therefore, there is a critical FZ size above which the pullout failure mode is ensured. The existence of a critical FZ size is reported in the literature[1,3–5,12].

As mentioned above, the weld nugget size, which is controlled by the welding variables (e.g., welding current, welding time and electrode pressure), is one of the main governing factors for the failure mode of the spot welds. Therefore, the variation of the failure mode can be related to the variation of the FZ size with the welding parameters. Regarding the effect of the welding parameters on the failure mode, the following point should be considered:

- As mentioned above, welds produced using low welding currents and low welding times exhibit a higher tendency to fail in IF mode. As can be seen in **Figure 6**, during a tensile-shear test, the driving force for the interfacial failure mode is the shear stress at the sheet/sheet interface in the weld nugget centerline, which depends on the area of the weld nugget in the plane of sheet/sheet interface. The shear stress at the sheet/sheet interface can be approximated using the following relation:

$$\tau = 4F/\pi D^2 \qquad (3)$$

  where F is the applied force and D is the weld-nugget size. Accordingly, as the weld-nugget size decreases, the shear stress experienced by the sheet/sheet interface increases. Therefore, decreasing the welding current and the welding time below a critical limit increases the risk of the interfacial failure mode due to the small weld-nugget size. The critical values to obtain PF mode are indicated in **Figure 5**.
- According to **Figure 5**, increasing the electrode pressure decreases the process window required to obtain the pullout failure mode. This adverse effect of the electrode force can be related to its negative effect on the weld-nugget size. Increasing the electrode force decreases the static (interfacial) electrical resistance and consequently decreases the generated heat and weld-nugget size. Therefore, on increasing the electrode force, a transition in the failure mode from the pullout to the interfacial mode was observed.

4.4 Final remark

As mentioned before, the fusion-zone size is one of the most important parameters controlling the failure mode of RSWs. Various industrial standards have recommended a minimum weld size for a given sheet thickness. For example, the American Welding Society[13] has recommended equation (4):

$$D = 4t^{0.5} \qquad (4)$$

According to equation (2), the minimum required weld-nugget size to ensure pullout failure mode for a 1.5-mm-thick DP980 sheet is 4.9 mm. According to the experimental data presented in this work, the minimum weld-nugget size required to ensure pullout failure mode is about 7 mm. Therefore, the conventional weld size recommendation of $D = 4t^{0.5}$ is not sufficient to guarantee the pullout failure mode for DP980 steel RSWs during a tensile-shear test. Indeed, metallurgical factors are ignored in this industrial criterion, for the sake of simplification. Pouranvari et al.[20] proposed a simple analytical model to predict the failure mode of spot welds during a tensile-shear test:

$$D_C = \frac{4t}{Pf} \cdot \frac{H_{PFL}}{H_{FZ}} \qquad (5)$$

where t is the sheet thickness, P is the porosity factor, f is the ratio of shear strength to tensile strength of the FZ, H_{FZ} and H_{PFL} are hardness values (HV) of the fusion zone and pullout failure location (i.e., softened HAZ in the case of DP980), respectively. According to this model, the failure mode of the spot welds is dictated by the fusion-zone size, the sheet thickness and the ratio of weld-nugget hardness to the failure-location hardness.

It should be noted that the $D = 4t^{0.5}$ criterion works well for spot welds of mild steel because the fusion zone has a significantly higher hardness. Typically, the fusion-zone hardness of mild-steel RSWs is about 2–3-times more than the base metal hardness[1]. Therefore, in the case of low-carbon steel, the pullout failure mode should be the desired failure mode for a strength estimation based on the fundamental mechanics[1]. However, the hardness ratio of dual-phase steel is lower compared to the low-carbon steels due to the higher hardness of the ferrite-martensite base metal. A low fusion-zone hardness to failure-location hardness increases the tendency of a spot weld to fail in the interfacial failure mode, during the tensile-shear test.

The susceptibility of dual-phase steel to the formation of shrinkage void/crack (**Figure 1**) during welding is another factor that can contribute to promoting the interfacial mode. The presence of the voids in the weld centerline can increase the critical fusion-zone size. This is due to the fact that the presence of the voids in the FZ decreases the area of the load-bearing surface in IF mode (i.e., sheet/sheet interface area). This leads to the development of a much higher shear stress at the interface and consequently promotes the IF mode. Dual-phase steels are prone to shrinkage void/crack formation in the FZ (for example, **Figure 2**) due to their rich chemistry in comparison to low-carbon steels[11]. The metallurgical characteristics of welds should be considered to predict and analyze the spot-weld failure mode more precisely.

5 CONCLUSION

Understanding the influence of the resistance spot-welding parameters on the failure mode of spot welds is a prerequisite for the development of the optimum welding conditions that ensure high levels of joint quality in autobody manufacture. The results of the present paper reveal how the failure mode is influenced by the main welding parameters, i.e., the welding current, the welding time and the electrode force. The following conclusions can be drawn from this study:

1. Increasing heat input caused by increasing welding current and welding current led to an enlargement of the weld nugget due to increasing the heat generated at the sheet/sheet interface.
2. Increasing the electrode force can increase the initial sheet/sheet contact areas and therefore decreases the sheet/sheet interfacial electrical resistively, which in turn leads to a reduction in the generated heat at the sheet/sheet interface. In the other words, increasing the electrode force increases the required welding current and the welding time required to melt the sheet/sheet interface.
3. The conventional weld-size recommendation of $D = 4t^{0.5}$ is not sufficient to guarantee the pullout failure mode for DP980 steel RSWs during a tensile-shear test. It is necessary to search for new weld-quality criterion for resistance-spot-welded dual-phase steels.
4. Increasing the welding current and the welding time at a constant electrode force leads to a change in the failure mode from the interfacial to the pullout failure mode.
5. Increasing the electrode pressure decreases the process window required to obtain the pullout failure mode (i.e., increasing the electrode force increases the minimum welding current and welding time required to obtain the PF mode).
6. The widest process window required to obtain the pullout failure mode occurs when welding using 4 kN and a welding time of more than 0.3 s.

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