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Failure Behavior of Three-Steel Sheets Resistance Spot Welds: Effect of Joint Design

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There is a lack of comprehensive understanding concerning failure characteristics of three-steel sheet resistance spot welds. In this article, macro/microstructural characteristics and failure behavior of 1.25/1.25/1.25 mm three-sheet low carbon steel resistance spot welds are investigated. To evaluate the mechanical properties of the joint, the tensile-shear test was performed in three different joint designs. Mechanical performance of the joint was described in terms of peak load, energy absorption, and failure mode. The critical weld nugget size required to insure pullout failure mode was obtained for each joint design. It was found that the joint design significantly affects the mechanical properties and the tendency to fail in the interfacial failure mode. It was also observed that stiffer joint types exhibit higher critical weld size. Fusion zone size along sheet/sheet interface proved to be the most important controlling factor of spot weld peak load and energy absorption.

Keywords failure behavior, resistance spot welding, three-sheet spot welding

1. Introduction

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 spot weld structural mechanical behavior. Therefore, the failure characteristics and performance of the spot welds significantly affect the durability and safety design of the vehicles (Ref 1-3).

Understanding the failure of two-sheet RSW is usually straightforward; however, problems arise when resistance spot welding three sheet of equal or non-equal thickness. In a three-sheet resistance spot weld, the weld nugget may grow from either the sheet/sheet interface or the geometrical center of the joint. One of the most important issues in resistance spot welding of three-sheet lap joints is insufficient growth of the weld nugget, which may cause problems in places needing larger weld nuggets (i.e., sheet/sheet interface). In many applications, spot welds between three sheets are needed due to limitations in structural design (e.g., at cross-member intersections) (Ref 4). In addition, with the increasing demand for lightweight vehicle structures, RSW of multiple stacks of similar and dissimilar work pieces is increasingly applied in some complex structures, such as front longitudinal rails, A-, B-, and C-pillars, and the bulkhead to inner wing (Ref 5). The majority of the research investigations have been carried out on the in the spot welding of two-sheet spot welding. Despite the applications of three-sheet RSWs, reports in the literature dealing with their welding behavior and mechanical behavior are limited (Ref 5-11). Although some studies (Ref 5-9) have been reported regarding weld nugget growth of three-sheet RSW, researches (Ref 10, 11) concerning mechanical properties and failure behavior of them are still lacking.

Harlin et al. (Ref 6) comprehensively investigated the weld nugget growth mechanism of two and three thickness lap joints. Harlin et al. (Ref 7) also studied the effect of electrode force on the weld nugget development of three thickness (3×1.5 mm) zinc-coated steel RSWs. They found that increasing the electrode force from 2.1 to 6 kN leads to a shift in the position of weld nugget formation from sheet/sheet interface to the center of the middle sheet. Shen et al. (Ref 5) and Ma et al. (Ref 8) investigated the weld nugget growth of three-sheet resistance spot welding through finite element simulation. Pouranvari and Marashi (Ref 9) investigated the effect of sheet thickness on the weld nugget growth behavior of three-sheet resistance spot welding. Jung et al. (Ref 10) investigated the selection criteria for joining three and four multithickness spot welds by analyzing the static strength and fatigue life of the joints. Choi et al. (Ref 11) investigated the fatigue behavior of triple thin sheet spot welds under the tensile-shear test. They found a linear relationship in log-log plot between the fatigue lifetime and the crack opening angle (COA) around the spot weld.

As mentioned above, the failure of spot welds significantly affects the vehicle crashworthiness. Therefore, prediction of failure characteristics of spot welds is of utmost importance. Although resistance spot welding has been used extensively, a simple failure criterion that is able to predict the failure strength of a spot weld when is subjected to various loading conditions does not exist. Moreover, the failure mechanism of three-sheet resistance spot welds is not well understood. Understanding the failure mode and failure mechanism of three-sheet resistance spot welds is a prerequisite to develop a failure criterion and to construct a numerical model for prediction the failure characteristics for three-sheet resistance spot welds. Therefore, the

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main concern of the present article is to investigate failure mechanism of three-sheet resistance spot welds. The effect of joint design on the failure mode transition behavior and mechanical properties of three-sheet drawing quality special killed (DQSK) low carbon steel resistance spot welds are investigated and analyzed.

2. Experimental Procedure

1.25-mm-thick uncoated DQSK low carbon steel of the type used in automotive industry was used in the investigation. The chemical composition of the steel is Fe-0.081C-0.21Mn-0.013Si. Spot welding was performed using a 120 kVA AC pedestal type resistance spot welding machine, controlled by a PLC. Welding was conducted using a 45° truncated cone RWMA Class 2 electrode with 8-mm face diameter. During all of experiments, electrode pressure, welding current, and holding time were kept constant at 3.5 bar, 11 kAs, and 0.4 s, respectively. Welding time was changed from 8 to 24 cycles (0.16 to 0.48 s). Ten samples were prepared for each welding condition including nine samples for the tensile-shear test (including three joint types) and one sample for metallographical investigation and measurement of weld size.

Samples for the metallographical examination were prepared using standard metallography procedures. Weld nugget (fusion zone) sizes were measured at sheet/sheet interface and geometrical center of the joint for all the samples on the metallographic cross sections of the welds. Vickers microhardness test was performed using an indenter load of 100 g for a period of 20 s to obtain diagonal hardness profile. The hardness indentations were spaced 0.5 mm apart. The spacing between indentations was large enough to avoid interaction between the work-hardening regions created around each indent.

To evaluate failure behavior and mechanical properties of the welded samples, three different joint designs were used. Joint designs and sample dimensions used in this study are shown in Fig. 1. The quasi-static tensile-shear tests were performed at a cross head of 2 mm/min with an Instron universal testing machine. Peak load (measured as the peak point in the load-displacement curve) and failure energy (measured as the area under the load-displacement curve up to the peak load) were extracted from the load-displacement curve. Failure mode was determined from the failed samples. In order to understand the failure mechanism, micrographs of the cross sections of the spot welded joints during and after the tensile-shear were examined by optical microscopy.

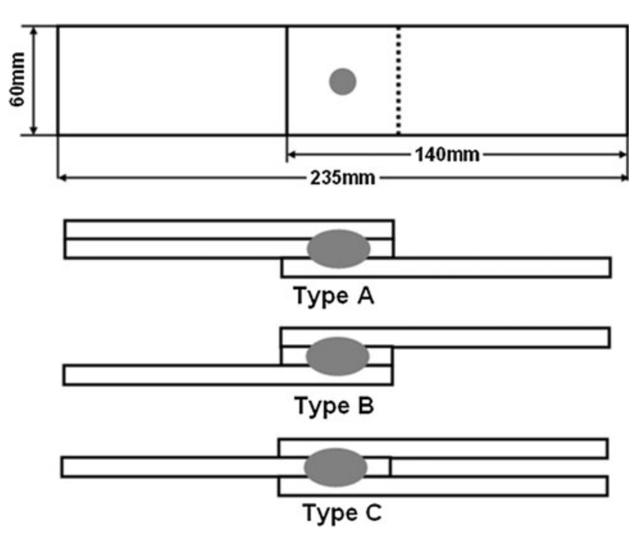

Fig. 1 Joint designs and sample dimensions

3. Results and Discussions

3.1 Joint Macro/Microstructure

A typical macrostructure of well developed three-sheet spot weld is shown in Fig. 2(a) indicating three distinct zones; denoted as fusion zone (FZ), heat affected zone (HAZ), and base metal (BM). The hardness profile of the joint is shown in Fig. 2(b). The DQSK BM microstructure (Fig. 2c) consists of ferrite grains and the corresponding hardness is about 110 HV. The FZ microstructure (Fig. 2d) is constituted of columnar structure composed of lath martensite, bainite, proeutectoid ferrite, and Widmanstatten ferrite with an average hardness of 258 HV. Martensite formation in fusion zone is attributed to the high cooling rate during resistance spot welding process (Ref 12) due to the presence of water cooled copper electrodes and their quenching effect as well as short welding cycle.

Weld fusion zone size (FZS) is the most important factor affecting spot weld performance (Ref 1-3). Therefore, there is a practical need to study the weld nugget growth to develop the optimum welding conditions which insure the high quality and mechanical performance of spot welds. Figure 3 shows weld nugget growth, i.e., the increase in weld nugget size as a function of welding time. Generally, weld nugget size increases with increasing welding time. However, as can be seen, FZS at sheet/sheet interface ($FZS_{S/S}$) is smaller than that of the geometrical center of the joint (FZS_{GC}). The effect of sheet thickness on the weld nugget growth behavior of three-steel sheet of equal thickness RSW has been studied in a previous work (Ref 9). It was found that there is a critical sheet thickness of 1.5 mm in which the FZS at sheet/sheet interface is nearly equal to the FZS at the geometrical center of the joint. Increasing the sheet thickness beyond the critical sheet thickness caused a shift in the location of weld nugget formation to the sheet/sheet interfaces. Below the critical sheet thickness the weld nugget growth in the geometrical center of the joint is higher than the sheet/sheet interface, as it is observed in present study. More detailed analysis on the weld growth mechanism is given elsewhere (Ref 9).

FZ size at sheet/sheet interface is the key controlling factors for mechanical properties and failure mode. Moreover, weld nugget resistance against interfacial failure mode is determined by $FZS_{S/S}$. Therefore, in the present case (1.25/1.25/1.25 mm RSW), in which the sheet thickness is below the critical sheet thickness, the weld nugget growth at sheet/sheet interface is not sufficient and therefore, the joint will be more prone to interfacial failure mode (i.e., crack propagation through FZ). In the remaining parts of this article, the effect of joint design on failure behavior of the similar three-sheet RSWs is discussed.

3.2 Failure Behavior

It is clearly seen that the stress distribution in the weldment in the investigated joint designs (A, B, and C) is different. Moreover, the stiffness of these joint designs and consequently

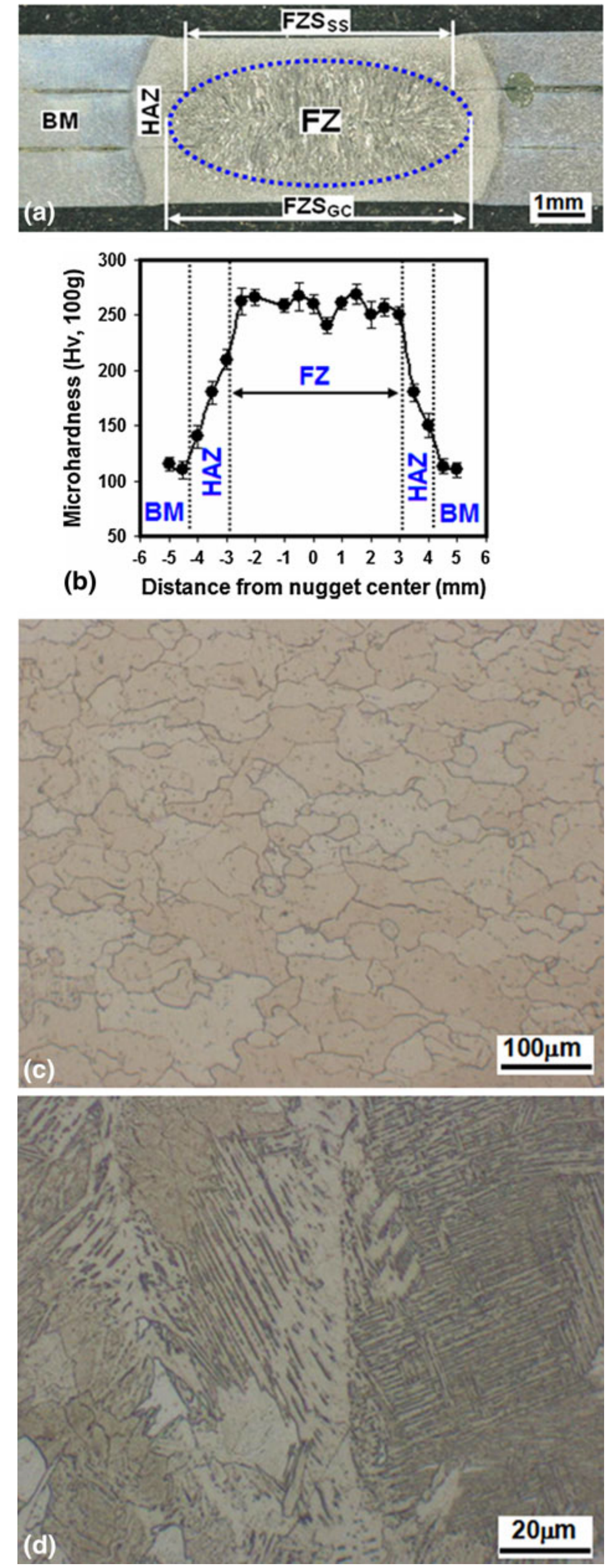

Fig. 2 (a) Overall macrograph: FZS_{SS}—fusion zone size at sheet/sheet interface, FSZ_{GC}—fusion zone size at geometrical center; (b) typical diagonal hardness profile; (c) BM microstructure; and (d) FZ microstructure of three-sheet RSW

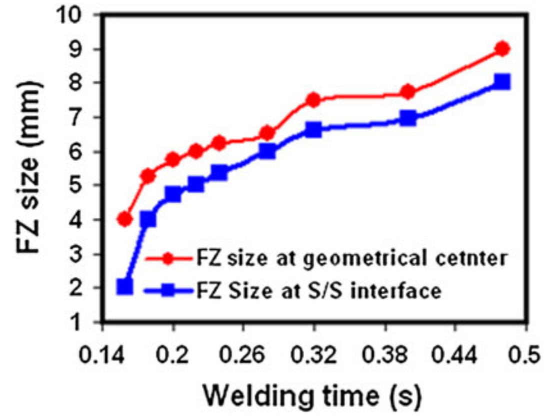

Fig. 3 Weld nugget growth curve for three-sheet RSW at geometrical center and sheet/sheet interface

the samples tendency to rotate during tensile-shear test is different. These factors significantly affect the failure behavior, strength, and the susceptibility of fail in interfacial mode. In the following sections, the different failure behaviors of spot welds in these three distinct joint designs are explained in terms of their stress distribution and stiffness. Detailed finite element modeling is needed to accurate determination of stress distribution.

3.2.1 Failure of Joint Type A. Figure 4(a) shows a simple model describing stress distribution at the interface and circumference of a three-sheet spot weld nugget. At the initial stage of loading, the nugget rotates by a couple created by two forces. The load on the nugget interface can be decomposed to two components: the tensile force F_n (= $F{\cdot}\sin\theta$) normal to the weld interface and the shear force F_s (= $F{\cdot}\cos\theta$) parallel to it. As can be seen in Fig. 4(a) (and Fig. 1a) a one-sheet leg (indicated by L_A) and a two-sheet leg (indicated by L_B) experience tensile stress. F_n and F_s are the main factor for PF and IF mode, respectively. Spot welds with small nugget sizes experience high shear stress which in turn leads to crack propagation through sheet/sheet interface in the weld nugget. A typical fracture surface of spot welds failed in interfacial mode is shown in Fig. 5. This type of failure was observed when the welding time is lower than 0.2 s. As can be seen interfacial failure accompanied with little plastic deformation indicating a low energy failure mode. Increasing weld nugget size, increases weld nugget resistance against interfacial failure. In the pullout failure mode (Fig. 4b), increasing tensile stress in A and B sites leads to local plastic deformation through thickness direction (Fig. 4c). As can be seen in Fig. 4(b), the one-sheet leg (L_A) and the two-sheet (L_B) leg are subjected to tensile stress and tend to neck. The pullout failure location is determined by the competition between necking of these two sites and failure is commenced wherever the stress level is higher. Since the experienced tensile stress in one-sheet leg (L_A) is higher than that of for two-sheet leg, one-sheet leg undergoes a severe necking leading to the initiation of the failure in this point (Fig. 4d). As can be seen from Fig. 4(c) and (d), necking location and pullout failure location is at the BM. This can be attributed to the low hardness of the BM in comparison to the HAZ and FZ which provide a preferential location for necking during the tensile-shear test. A similar failure mechanism (through thickness necking) was observed in two thickness resistance spot welds during the tensile-shear test (Ref 13, 14). Fracture followed by crack propagation in nugget circumference and the final separation (Fig. 4e) occurred by sheet tearing in the upper sheet (one-sheet leg).

3.2.2 Failure of Joint Type B. Figure 6(a) shows a simple model describing stress distribution at the interface and circumference of a three-sheet spot weld nugget in type B of joint design. On loading, nugget experiences significant rotation due to bending moment and the low stiffness of this joint design. The shear stress at sheet/sheet interface, which is the driving force for the IF mode, is a function of the weld nugget rotation. The more rotation, the lower shear stress acts on the sheet/sheet interface. Upper and lower sheets are subjected to an equal tensile stress and tend to neck. Spot welds with small nugget size tend to fail in the IF mode (see Fig. 6b) as a result of the following facts: (i) smaller nuggets experience higher shear stress due to small area of the weld nugget in the sheet/sheet plane and (ii) smaller nuggets rotate less than the larger ones; consequently, the shear stress experienced by the sheet/sheet

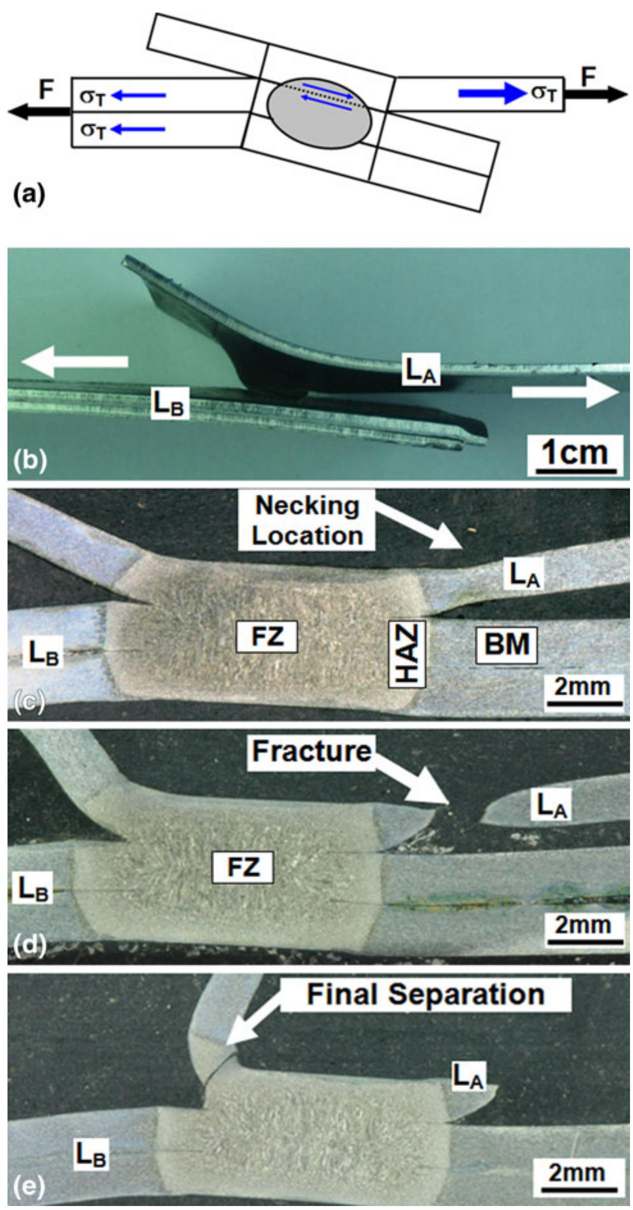

Fig. 4 Type A joint design. (a) A simple model describing stress distribution at the interface of the sheets and at weld nugget periphery, (b) pullout failure mode, weld nugget is pulling out from upper sheet, (c) macrograph of fracture cross section showing initial necking, (d) macrograph of fracture cross section showing failure in the base metal region of the one-sheet leg of the joint, (e) macrograph of fracture cross section showing final failure: L_A and L_B are one-sheet leg and two-sheet leg, respectively

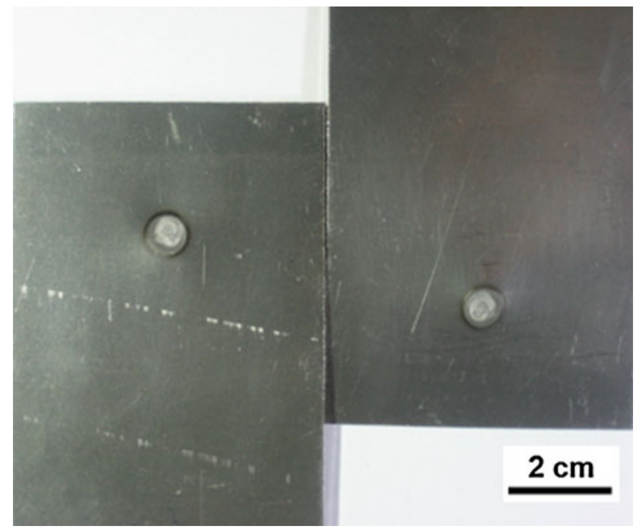

Fig. 5 A typical fracture surface of spot weld failed in interfacial failure mode: failure is occurred via crack propagation through sheet/sheet interface. Almost no plastic deformation is obvious which resulted in reduced energy absorption

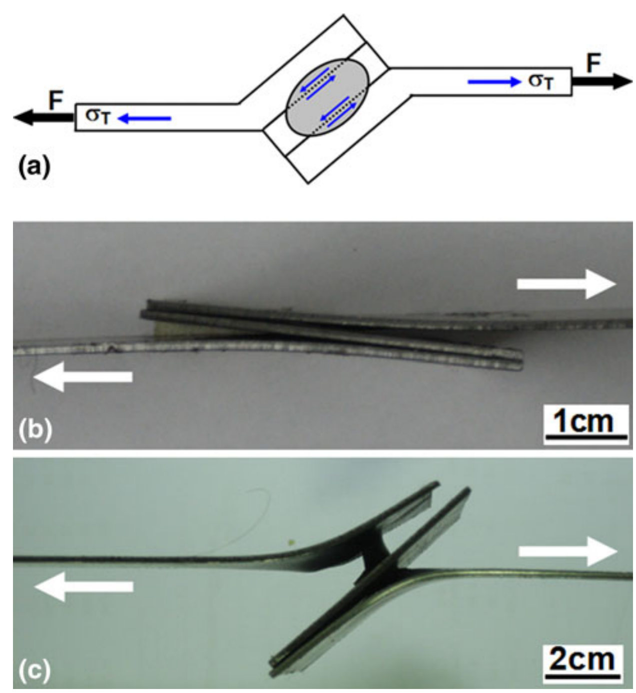

Fig. 6 Type B joint design (a) A simple model describing stress distribution at the interface of the sheets and at weld nugget periphery, (b) interfacial failure mode, sample experienced small rotation during loading, (c) pullout failure mode, weld nugget is pulling out from upper sheet, sample experienced large rotation during loading

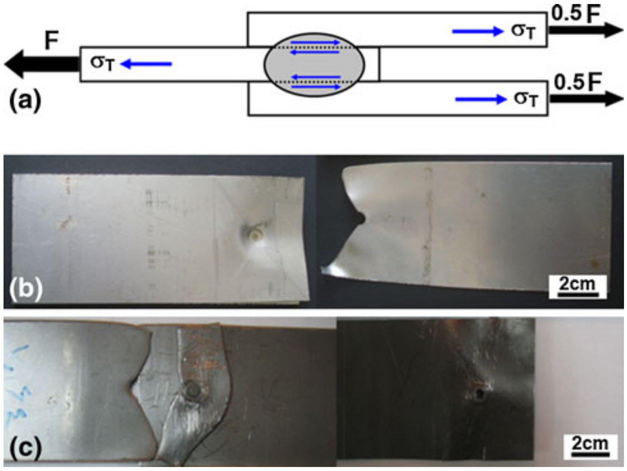

Fig. 7 Type C joint design. (a) A simple model describing stress distribution at the interface of the sheets and at weld nugget periphery, (b) sheet teasing in base metal in specimen width direction, (c) sheet tearing and nugget pullout

interface is higher compared to large nuggets which are subjected to higher rotations during loading. Fracture in pullout mode is initiated by thickness necking at the upper sheet, and then the neighboring BM tears in an elliptical form (see Fig. 6c).

3.2.3 Failure of Joint Type C. Figure 7(a) shows a simple model describing stress distribution at the interface and circumference of a three-sheet spot weld nugget in type C of joint design. Unlike to types A and B, owing to absence of any momentum, the nugget experiences no rotation during loading and therefore, the sheet/sheet interface is subjected to nearly pure shear. The high shear stress at sheet/sheet interface leads to IF mode, unless the weld nugget size at sheet/sheet interface is sufficiently large to avoid shear fracture from interface and promotes the initiation of necking in through the thickness direction of the middle sheet (i.e., where the tensile stress is the highest). Similar to other joint types, the necking location is in the BM. The final fracture occurs by propagation of formed crack in the specimen's width so that the whole specimen thoroughly fails (Fig. 7b). In some cases (see Fig. 7c), before completion of crack propagation in width direction, the process of nugget pulling out from upper/lower sheet is initiated and leads to production of a nugget bottom and a hole.

3.3 Effect of Joint Design on the Failure Mode Transition

The effect of joint type on the failure mode is shown in Fig. 8. As can be seen, there is a transition in failure mode from IF to PF in all types of the join designs. According to Fig. 8, for each type of the joint designs, the failure mode was changed from IF to PF by increasing the welding time. In order to avoid IF mode, a minimum welding time of 0.2, 0.18, and 0.28 s should be used for welding of type A, type B, and type C specimens, respectively. The driving forces for the interfacial and pullout failure modes is the shear stress at sheet/sheet interface and the tensile stress at the weld nugget borders, respectively. Each driving force has a critical value and the failure mode is determined by the driving force which reaches its respective critical value sooner. Weld nugget size is the most important parameter in determining the stress distribution. For the welds with small nugget size, the shear stress reaches its critical value before tensile stress causes necking in the BM.

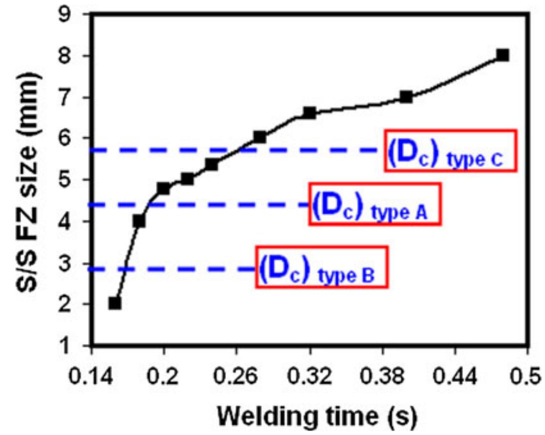

Fig. 8 Effect of welding time and FZ size on the failure mode and the critical FZ size required to avoid IF mode

Therefore, failure tends to occur under interfacial failure mode. Increasing weld nugget size, increases the weld nugget resistance against interfacial (i.e., shear) failure. Hence, there is a critical weld nugget size (D_C) beyond which, pullout failure mode is dominated. It is well documented that there is a critical FZ size beyond which spot welds tend to fail in PF mode and below that spot welds are liable to fail in IF mode (Ref 1-3, 13). The critical FZ size (defined as the FZ size between the maximum weld size leading to IF mode and minimum weld size leading to PF mode) is represented in Fig. 8. Type C welds show the highest tendency to fail in the interfacial mode. However, for type B joints, the PF mode was obtained at much smaller FZ sizes. The tendency to fail in the IF mode is increased in order of: type B, type A, and type C. To explain the IF to PF transition behavior, the following points should be considered:

(i) In the tensile-shear test, the driving force for the IF mode is the shear stress at the sheet/sheet interface which depends on the area of the weld nugget in the sheet/sheet plane. The higher the shear stress at sheet/sheet interface, the higher the tendency to fail in the IF mode.
(ii) The driving force for the PF mode is the tensile stress at the nugget circumference. Tensile stress is mainly induced by the bending moment as a result of rotating of the weld nugget during the shear-tensile test. There is a relationship between the degree of rotation during the tensile-shear test and the failure mode (Ref 15). The stiffer the sample (i.e., less rotation), the higher the susceptibility to the interfacial failure mode. In other words, the higher the stiffness, the lower the tendency to fail in the PF mode.
(iii) According to the stated propositions, the highest D_C of type C can be attributed to its high stiffness. As can be seen in Fig. 7 the rotation angle of this type is smaller than the others. Indeed, in type C the stress state at the sheet/sheet interface in nearly pure shear. On the other hand, the low D_C of type B can be related to its low stiffness and large rotation experienced during loading.

3.4 Effect of Joint Design on Mechanical Strength

Peak load of spot welds (maximum force that a given spot weld can withstand without fracture) is compared for the

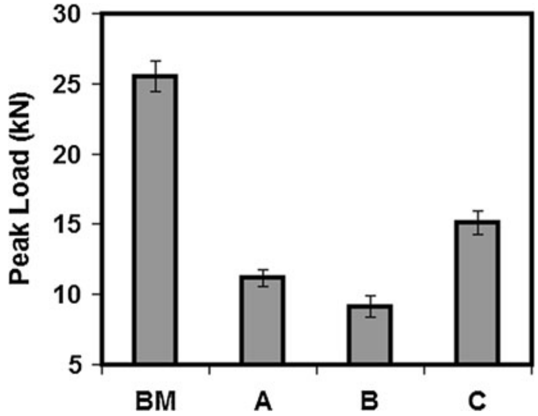

Fig. 9 Effect of joint design on the strength three-sheet RSWs, load bearing capacity of the base metal (BM) is also shown for the purpose of comparison

samples welded at 0.4 s welding time. In this welding condition, the FZ size at sheet/sheet interface is about 7 mm and all combinations were failed in the PF mode. Figure 9 shows the effect of joint design on the load bearing capacity of the joint. Since, the geometrical attributes of the welds are constant for all joint designs; the different mechanical response of the joints is attributed to the differences in their stress distribution and stiffness. As can be seen in Fig. 9, the peak load of the type C is higher than that of the other types. The peak load in the tensile-shear test corresponds to the necking initiation in the BM. Therefore, the higher peak load of type C can be attributed to its higher stiffness which can result in the delayed necking and consequently, to an increase in the load bearing capacity of the joint. The low peak load of type B is a result of the easy rotation inherent to this joint design which causes premature necking in the BM. It should be noted that more detailed analysis of the mechanical strength results needs more accurate stress analysis in the weldment which can be determined using finite element modeling.

It is of note that in all cases the load bearing capacity of the joints is lower than the BM. The ultimate tensile strength of the investigated DQSK sheet is 340 MPa; therefore, the peak load of a homogeneous sheet (i.e., without weld) with cross section of 1.25×60 mm^2 is 25.5 kN. Therefore, it can be concluded that the presence of the weld including microstructure gradients in the FZ and HAZ reduces the overall load bearing capacity. At the best condition, for type C joint, in the tensile-shear test the load bearing capacity of the welded joint is reduced by about 40% compared to the weld free sheet. These results clearly indicate that microstructure/properties gradients associated with spot welds have a significant effect on the mechanical behavior of spot welded sheets.

3.5 Effect of FZ Size on the Mechanical Properties

To study the effect of FZ size on the mechanical properties of the joint, the type A joint design was selected. The effect of FZ size on the peak load and energy absorption is shown in Fig. 10. The mechanical strength of spot welds is determined mainly by the weld nugget size at sheet/sheet interface. As can be seen there is a direct relationship between mechanical performance (peak load and energy absorption) and FZ size along the sheet/sheet interface. This is due to the fact that increasing the weld size leads to an increase in the overall bond area.

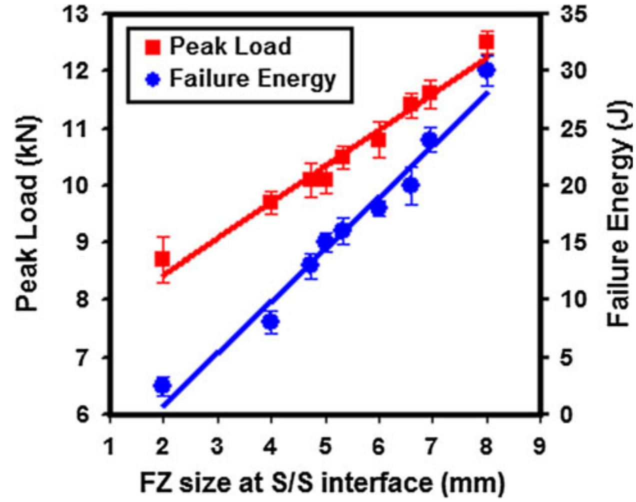

Fig. 10 Effect of FZ size on the peak load and failure energy of three-sheet RSWs in type A joint design

4. Conclusions

In this article, the effect of three distinct joint designs on the failure characteristics of three-sheet resistance spot welded low carbon steel is experimentally investigated. The different mechanical response of joint designs can be explained in terms of the stress distribution and stiffness of each joint type. From this research the following conclusions can be drawn:

1. Interfacial failure mode is controlled by weld nugget size along the sheet/sheet interface. As observed in this study, longer welding times is required to insure sufficient weld nugget growth along the sheet/sheet interface compared to the required time for nugget growth along geometrical center of the joint. Transition in failure mode from interfacial mode to pullout mode is observed by increasing the weld nugget size along the sheet/sheet interface.
2. The joint design has a significant effect on the failure mode transition behavior. The minimum weld nugget size (D_C) required to obtain pullout failure mode during the tensile-shear test increases in order of: type B, type A, and type C. A direct relationship between D_C and the stiffness of the joint design is found. Rotation of weld nugget during loading reduces the effectiveness of the applied shear stress at the sheet/sheet interface and hence reduces the tendency to fail in the interfacial failure mode.
3. Load bearing capacity of the welds is a function of the joint design stiffness. The peak load of the welds in pullout failure mode increases from B type to type A and finally type C.
4. There is a direct relationship between the FZS along the sheet/sheet interface and the mechanical performance (i.e., peak load and energy absorption) of the three-sheet spot welds.

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