Resistance Spot Welding Characteristic of Ferrite-Martensite DP600 Dual Phase Advanced High Strength Steel-Part II: Failure Mode

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Abstract: Failure mode is a qualitative measure of resistance spot weld performance. To ensure reliability of resistance spot welds during vehicle lifetime, process parameters should be adjusted so that the pullout failure mode is guaranteed. Dual phase (DP) steel resistance spot welds are prone to interfacial failure mode. In this paper the failure mode of DP600 dual phase steel resistance spot welds during quasi-static is investigated. It was found that the failure mode was altered from interfacial to pullout failure mode by increasing welding current. Results should that the conventional recommendation of 4t (t is sheet thickness) for weld sizing is not sufficient to obtain pullout failure mode during the tensile-shear test of DP resistance spot welds. The minimum required fusion zone size to obtain pullout failure mode is estimated using an analytical mode.

Key words: Dual phase steel - Resistance spot welding - Failure mode

INTRODUCTION

There is an increasing demand for high-strength steel sheets in the automotive industry, in order to improve the fuel efficiency, occupant’s safety and reduction of auto body weight. 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 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]. Considering 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 litterateur, problems associated with the resistance spot welding of DP steels can be summarized as follows [3-12]:

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

Failure mode of resistance spot welds (RSWs) is a qualitative measure of the joint quality. Fig.1 shows typical fracture mode during mechanical testing of spot weld. Basically, spot welds can fail in two distinct modes [13-15]:

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

Failure mode can significantly affect the load bearing capacity and energy absorption capability of RSWs. Spot weld failure mode is a qualitative measure of the weld quality. Failure mode of RSWs can significantly affect the load carrying capacity and energy absorption capability. The shape of load displacement curves under shear tensile test for both interfacial and pullout modes are drawn schematically in Fig. 2. Generally, the pullout mode is the preferred failure mode due its higher associated plastic deformation and energy absorption [16]. Thus, vehicle crashworthiness, as the main concern in the automotive design, can dramatically reduce if spot welds fail via 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
Failure of the resistance spot welds is a complicated phenomenon. Failure mode and failure mechanism are largely dependent upon the complex interplay between the weld geometry, materials properties, test geometry and the stress state in each weld [5-8].

RSW of AHSS exhibits higher tendency to fail in interfacial failure mode than traditional steels (i.e. low carbon and high strength low alloy steels) [8-10]. 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 nontraditional 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. In this paper, the failure mode of DP600 resistance spot welds under tensile-shear test is investigated. Minimum fusion zone size required to ensure pullout failure mode is estimated using an analytical mode.

**EXPERIMENTAL PROCEDURE**

2 mm thick DP600 dual phase steel sheets was used as the base metal. Resistance spot welding was performed using a 120 kVA AC pedestal type resistance spot welding machine, controlled by a programmable logic controller (PLC) operating at 50 Hz. Welding was conducted using a 45-deg truncated cone Class 2 electrode of Resistance Welding Manufacturing Alliance (RWMA) with 8-mm face diameter.

To study the effects of the welding conditions on the weld failure mode, several welding schedules were used. Electrode force and holding time were selected based on the thickness of the base material and were kept constant at 5.1 kN and 0.2s, respectively. Welding current was increased step by step from 7.5 to 12 kA with step size of 0.5 kA at welding times of 0.5s. Four samples were prepared for each welding condition including three samples for the tensile-shear test and one sample for metallographical investigation and measurement of weld size.

In order to evaluate the failure mode of the spot welds, the tensile-shear test was performed. Samples were prepared according to American welding society (AWS) standard [18]. Coupon dimension for the tensile-shear are shown in Fig.3. Failure modes of the spot welded specimens were determined by the examination of the fractured samples.

**RESULTS AND DISCUSSION**

**Observed Failure Modes:** Two distinct failure modes were observed during tensile-shear test of DP600 resistance spot welds. Fig.4 shows a typical macrostructure of DP600 and the schematic failure path during IF (Path A) and PF mode.
(Path B) during loading. It has been shown experimentally that under tensile-shear loading, the pullout failure is occurred in the softer region of the spot weld [19-20]. According to hardness profile of DP600 spot welds the base metal region exhibit the lowest hardness. Therefore, the failure initiation site in pullout mode of DP600 is base metal region.

**Effect of FZ Size on the Failure Mode:** Fig. 5 shows the effect of welding current and FZ size on the failure mode. As can be seen, increasing welding current beyond 10 kA alters the failure mode from interfacial to pullout mode. Also, according to Fig. 5, increasing FZ size led to transition in failure mode from interfacial to pullout mode. According to Fig. 5, the maximum FZ size led to fail in interfacial mode is 8.4 mm and the minimum FZ size led to fail in pullout mode is 9.1 mm.

The effect of FZ size on the failure mode can be explained in terms of stress distribution in the spot weld during the tensile-shear test. Fig. 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 which 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 mode, 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 weld nugget size are the most important governing parameters of the failure mode of resistance spot welds. Weld nugget size is the most important parameter determining stress distribution. For those welds with small weld size, the shear stress reaches its critical value before tensile stress causing failure in the circumference of the FZ. Therefore, failure tends to occur under interfacial failure mode. Increasing FZ size, increases the weld nugget resistance against interfacial (i.e. shear) failure. Therefore, there is a critical FZ size above which pullout failure mode is ensured. The existence of a critical FZ size is reported in the literature [5, 8, 11, 13].

**Critical Fz Size:** FZ size the most important parameter controlling the failure mode of RSWs. Various industrial standards have recommended a minimum weld size for a given sheet thickness. American Welding Society [18] has recommended equation (1):

\[ D = 4t^{0.5} \]  
(1)

Where, \( t \) is sheet thickness and \( D \) is weld nugget size.

According to Japanese JIS Z3140 [21] and the German DVS2923 [22] standards the required weld size is specified according to the equation (2)

\[ D = 5t^{0.5} \]  
(2)

According to equation (1) and equation (2), the minimum required weld nugget size to ensure pullout failure mode for 2 mm thick DP600 sheet, is 5.6 and 7.1 mm, respectively. According to experimental data presented in this work, minimum weld nugget size required to ensure pullout failure mode is 9 mm. Therefore, the conventional
weld size recommendation of $D=4t^{0.5}$ and $D=5t^{0.5}$ are not sufficient to guarantee the pullout failure mode for DP600 steel RSWs during tensile-shear test. Indeed, metallurgical factors are ignored in this industrial criterion, for the sake of simplification.

In this section, a simple analytical model is proposed to predict joint failure mode during the tensile-shear testing of DP600 steel resistance spot welds. Fusion zone size is the most important parameter determining stress distributions in sheet/sheet interface and weld nugget circumference. For small weld nuggets, before tensile stress causes necking shear stress reaches its critical value, as a result failure tends to occur under the interfacial failure mode. Therefore, in this section an attempt was made to estimate a minimum fusion zone size necessary to ensure nugget pullout failure mode during the tensile-shear test.

Considering nugget as a cylinder with (D) diameter, failure load at the interfacial failure mode (PIF) could be expressed as equation (2) assuming uniform distribution of shear stress in the weld interface:

$$p_{IF} = \left(\frac{\pi D^2}{4}\right)\tau_{FZ}$$

(2)

where: $\tau_{FZ}$ is the shear ultimate strength of the FZ.

In the pullout failure mode, it is assumed that failure occurs when maximum radial stress at the circumference of one half of the cylindrical nugget reaches the ultimate strength of the failure location. Therefore, equation (3) is suggested for the pullout failure of spot weld in the tensile-shear test.

$$p_{PF} = \pi D\sigma_{PFL}$$

(3)

where: $\sigma_{PFL}$ is the ultimate tensile strength of pullout failure location.

Failure is a competitive process, i.e. spot weld failure occurs in a mode which requires smaller force, i.e. force that will be first attained. A critical fusion zone size ($D_c$) can be defined which determines which one of the failure modes happens. Spot welds with $D<D_c$ tend to fail via interfacial failure and welds with $D>D_c$ tend to fail via nugget pullout failure mode.

Therefore, to obtain critical nugget diameter, $D_c$, equations (2) and (3) are intersected resulting in equation (4):

$$D_c = 4t\left(\frac{\sigma_{UTS}}{\tau_{FZ}}\right)$$

(4)

Direct measurement of the mechanical properties of different regions of spot weld is difficult. It is well known that there is a direct relationship between steels tensile strength and their hardness. Also, shear strength of materials can be related linearly to their tensile strength by a constant coefficient, $f$. According to Tresca criterion is 0.5 [23]. On that account, equation 4 can be rewritten as follows:

$$D_c = 4t\frac{H_{FL}}{f\times H_{FZ}}$$

(5)

According to equation (5), the critical fusion zone size depends on the FZ and failure location hardness, in addition to sheet thickness. For a constant sheet thickness, decreasing the ratio of fusion zone hardness to failure location hardness raises its tendency to fail under the interfacial failure mode (i.e. larger $D_c$).

In the case of DP600 steel, average FZ hardness is approximately 380 HV. The failure location in pullout mode of DP600 during tensile-shear test is the base metal. This is due to the fact that low hardness of the base metal rather than HAZ and fusion zone can provide a preferential location for necking during the tensile-shear test. The hardness of the pullout failure location (i.e. base metal) is about 200HV. Therefore, the hardness ratio of FZ to failure location is about 1.9. By substituting these values in equation 5, critical fusion zone size is calculated to be 8.43 mm. Fig. 6 shows that this value separates the interfacial and nugget pullout failure modes.

According to the mode, failure mode of spot welds dictated by the fusion zone size, sheet thickness and the ratio of weld nugget hardness to failure location hardness. Low fusion zone hardness to failure location hardness increases the tendency of spot weld to fail in the interfacial failure mode, during the tensile-shear test. It should be noted that $D=4t^{0.5}$ criterion works well for spot welds of mild steel because the fusion zone has a significantly higher hardness [5]. Typically fusion zone hardness of mild steel RSWs is about 2-3 times more than base metal hardness [5, 15, 20]. Therefore, in the case of low carbon steel, pullout failure mode should be the desired failure mode for strength estimation based on the fundamental mechanics. According to the results of this study, metallurgical characteristics of welds should be considered to predict and analyze the spot weld failure mode more precisely.
CONCLUSIONS

- From this study the following conclusions can be drawn:

- Increasing welding current leads to alter failure mode from interfacial failure mode to pullout mode.
- A minimum FZ size of 9.1mm was required to ensure pullout failure mode during the tensile-shear test of DP600 resistance spot welds.
- The conventional weld size recommendation of $D = 4t^{0.5}$ is not sufficient to guarantee the pullout failure mode for DP600 steel spot welds during tensile-shear test.
- The proposed analytical model successfully predicts the critical weld fusion zone size for DP600 steel resistance spot welds. According to this model, low fusion zone hardness to failure location hardness ratio increases the tendency of spot weld failure to occur in the interfacial failure mode during the tensile-shear test. Metallurgical characteristics of welds should be considered to predict and analyze the spot weld failure mode more precisely.

REFERENCES

22. German Standard, Resistance Spot Welding, DVS 2923.