Resistance Spot Welding Characteristic of Ferrite-Martensite DP600 Dual Phase Advanced High Strength Steel-Part III: Mechanical Properties

M. Pouranvari and E. Ranjbar Noodeh

1Young Researchers Club, Dezful Branch, Islamic Azad University, Dezful, Iran
2Young Researchers Club, East Tehran Branch, Islamic Azad University, Tehran, Iran

Abstract: This paper addresses the mechanical properties of DP600 dual phase resistance spot welds during quasi-static tensile-shear test. The mechanical properties were described in terms of peak load and energy absorption. It was shown that the fusion zone size is the most important controlling factor of spot weld peak load and energy absorption. It was shown that heavy expulsion and associated large electrode indentation can reduce load carrying capacity and energy absorption capability of DP600 spot welds.

Key words: Resistance spot welding · DP600 · Peak load · Failure Energy · Expulsion

INTRODUCTION

Ferrite–martensite dual phase (DP) steel is one of the most common AHSS steels which are currently used in automotive industry [1]. Intercritical annealing followed by rapid cooling produces ferrite-martensite DP steels. During the intercritical annealing small pools of austenite are formed in the ferrite matrix, which subsequently transform into martensite upon rapid cooling [2]. In this combination of two phases, martensite contributes with high strength and ferrite matrix provides good elongation that can produce a good combination of strength and ductility for applications that required good formability. This unique composite microstructure offers other interesting mechanical properties such as continuous yielding, low yield stress to tensile strength ratios and high initial work-hardening rate [3-4].

Quality and performance of resistance spot welds (RSWs) are very important for determination of durability and safety design of the vehicles. Generally, there are three measures for quality evaluation of resistance spot welds including physical weld attributes (e.g. weld nugget size, electrode indentation, etc), mechanical properties and failure mode [5-6]. Significant works have been carried out on the welding behavior and mechanical properties of low carbon and HSLA steels [5-12]. In many studies, the effects of process parameters including welding current, welding time, electrode force, holding time and electrode geometry on the physical weld attributes and mechanical properties were studied for a given steel base metal. Through these researches, it is well established that the geometrical attributes of spot welds, particularly weld nugget size, are the most important controlling factors determining the mechanical strength of RSWs [5-12]. In this regard, weld nugget size has been included in several empirical relations. For example, Heuschkel [7] developed empirical relations among the tensile-shear strength (P), weld nugget size diameter (D), base metal tensile strength (σtBM), sheet thickness (t) and base metal chemical composition (C, Mn):

\[ P = D[ \alpha - \beta(C + 0.05Mn)] \sigma_{tBM} \] (1)

Where \( \alpha \) and \( \beta \) are material dependent coefficients. Other researchers have developed similar relations. For example, Sawhil and Baker [8] developed the following relation for the tensile-shear strength of spot welds:

\[ P = ftD \sigma_{tBM} \] (2)

Where, \( f \) is a materials dependent coefficient, with a value between 2.5 and 3.1.

Recently, Radakovic and Tumuluru [13] through modeling of actual test results of dual phase steels showed that the failure load for a full-button pullout (Pfp) is given by

\[ P_{fp} = 2.54tD \sigma_{BM} \] (3)
Zuniga [14] and Zhou et al. [15] mentioned that for the sake of completeness in analyzing the mechanical behavior of RSWs, the energy absorption capability of resistance spot welds should be considered, in addition to peak load. Zhou et al. [15] through computer simulation using the concept of design of experiments developed relationship for peak load and energy absorption of spot welds taking into account the electrode indentation depth and HAZ size in addition to weld size.

In this part, the mechanical properties of DP600 resistance spot welds during the tensile-shear test are investigated and analyzed. Effects of expulsion on the peak load and energy absorption of the welds are also analyzed.

**EXPERIMENTAL PROCEDURE**

2 mm thick deep drawing specially killed low carbon steel (LCS) and 2 mm thick DP600 ferrite-martensite dual phase steel sheets were used as the base metals. Resistance spot welding was performed using a PLC controlled, 120-kVA AC pedestal type resistance spot welding machine. Welding was conducted using a 45-deg truncated cone RWMA Class 2 electrode with 8-mm face diameter.

To study the effects of welding conditions on the weld mechanical performance, several welding schedules were used. 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 gradually from 7.5 to 12 kA at welding times of 0.5s. Critical welding conditions leading to expulsion were recorded. Four samples were prepared for each welding condition including three samples for the tensile-shear test and one sample for metallographic investigation and measurement of weld size.

In order to evaluate the mechanical performance and failure mode of the spot welds, the tensile-shear test was performed. According to the AWS standard [16], 140×60 mm samples were sheared and a single spot weld was made at the center of an overlapped area with a width of 45 mm. The tensile-shear tests were performed at a cross head of 10 mm/min with an Instron universal testing machine. Load-displacement curves were recorded during tensile-shear tests. Fig. 1 shows a typical load-displacement curve. Peak load (measured as the peak point in the load-displacement curve) and the failure energy (measured as the area under the load-displacement curve up to the peak load) were extracted from the load displacement curve (Fig. 1). The failure energy is calculated up to peak load not up to failure. This was due to the fact that total energy when the specimen finally fails is not quite relevant to a weld’s performance—it reflects more on the influence of the specimen than the spot weld [17]. The data points for peak load and failure energy are averages of the measured values for the three specimens. Failure modes of the spot welded specimens were determined by examination of the fractured samples. Samples for the metallographical examination were prepared using standard metallographic procedure. 4% Nital etching reagent was used to reveal the macrostructure of the samples. Physical weld attributes including fusion zone (FZ) sizes and average indentations depths (t-indent) caused by electrode pressure were measured for all the samples on the metallographic cross-sections of the welds FZ size is defined as the width of the weld nugget at the sheet/sheet interface in the longitudinal direction. Indentation depth is expressed as a percentage of the sheet thickness.

**RESULTS AND DISCUSSION**

**General Comments:** Mechanical performance of spot welds is described in terms of load bearing capacity and energy absorption capability. These properties depend on the following factors:

**Weld Nugget Size:** Weld nugget size is the most important parameter governing the mechanical properties of the spot welds [6-10]. FZ size, which determines the overall bonding area of the joint, is controlled by heat input rate which in turns is governed by the welding parameters. Generated heat during resistance spot welding can be expressed as follows [18]:

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Fig. 1: A typical load-displacement curve along with the extracted parameters; $P_{\max}$: Peak load, $W_{\max}$: Energy absorption.
Where, $Q$, $R$, $I$, and $t_w$ are generated heat, electrical resistance, welding current and welding time, respectively. Therefore, the three main parameters affecting the weld nugget growth are welding current, welding time and electrical resistance.

**Indentation Depth:** Electrode indentation, which can affect the mechanical properties of the spot welds, depends on electrode pressure and the temperature of electrode/sheet interface [18].

**Strength and Ductility of the Failure Location:** Peak loads of RSWs also depend on the failure location strength. Failure energy of RSWs, measured as the area under the load-displacement curve up to the peak point, can be expressed as follows:

\[ \text{Energy Absorption} = \int_{\alpha}^{l_{\text{max}}} F \, dl \propto P_{\text{max}} \times l_{\text{max}} \]  

(5)

Where, $P_{\text{max}}$ is the peak load and $l_{\text{max}}$ is maximum displacement, corresponding to the peak load. Maximum displacement ($l_{\text{max}}$) which represents ductility of spot welds depends on the ductility of failure location. Therefore, energy absorption depends on the factors governing the peak load and ductility of the failure location.

If spot welds fail in the IF mode, the strength and ductility of the FZ are important for the mechanical properties of the weld. If spot welds fail in the PF mode, the strength and ductility of the failure location (base metal in the case of DP600 RSWs [19]) determine the mechanical properties of the spot weld. In this case, the FZ properties are not critical for determination of the weld mechanical properties. In the following section, the effect of welding parameters on the peak load and energy absorption of the spot welds is discussed in the light of the above factors.

**Effet of Welding Current on the Mechanical Properties:**
To complete exploration of the mechanical properties of the spot welds, their energy absorptions were also measured, in addition to the peak load. Failure energy is a measure of the energy absorption capability of the welds whose higher value demonstrates an increase in weld performance reliability against impact loads such as accidents [17]. It has been shown that there is a direct relationship between the failure energy in static tensile-shear test and the impact tensile-shear test [20].
Fig. 2 shows the effect of welding current on the peak load of welds indicating that that generally increasing welding increases the load bearing capacity. However, at high heat input welding condition (i.e. welding current beyond 11kA), peak load is reduced.

Fig. 3 shows the effect of welding current on the failure energy indicating that increasing heat input caused by increasing welding current increases the energy absorption capability of the welds. However, at high heat input welding condition (i.e. welding current beyond 11kA) energy absorption is significantly reduced.

Mechanical Properties in Expulsion Free Welds:
To examine the relationship between the peak load (and the failure energy) and the weld nugget size, a scatter plot of peak load (and failure energy) vs. weld size was constructed and a trend line was added to the scatter plot to show the general trend (Fig. 4 and Fig. 5). Fig. 4 shows the effect of FZ size on the peak load. As can be seen, there is a direct correlation between FZ size and peak load. To establish a relationship between weld attributes and peak load, the following relation was developed using mathematical regression:

\[ \text{Peak Load} = 1.5D + 11.1 \]  

(6)

Fig. 5 shows the effect of FZ size on the failure energy indicating that there is a direct correlation between FZ size and the failure energy. To establish a relationship between weld attributes and failure energy, the following relation was developed using mathematical regression:

\[ \text{Failure Energy} = 6.35D - 12.8 \]  

(7)

The peak point in load-displacement plot of tensile-shear test corresponds to the point of crack propagation through the weld nugget, for interfacial mode and to the necking/cracking point at failure location, for pull out mode. For interfacial mode, the bigger the nugget size the higher is the interfacial resistance to shearing. The effect of FZ size in PF mode is explained as follows: The characteristic mechanisms of the PF mode in the tensile-shear testing include rotation of the weld nugget and stretching, thinning and necking in the nugget circumference [14, 17]. Indeed, even though the loading condition is nominally shear, the pullout failure is predominantly tensile through rotation. Increasing nugget diameter increases the stiffness of the joint and thus reducing the tendency to rotating. The less nugget rotating, the lower tensile stress subjected to the nugget circumference is. Therefore, increasing weld nugget size increases load bearing capacity of the spot welds in pullout mode. According to Fig. 4 and Fig. 5, fusion zone size is the most important controlling parameter of peak load and energy absorption of the DP600 spot welds. Similar conclusion was obtained for galvanized low carbon steel [5], HSLA steels [12], austenitic stainless steels [21], TRIP800 steel [22] and DP800 [23]. In summary, increasing welding current results in higher heat generation at the faying interface resulting in the formation of larger fusion zone and increases overall bond area. Moreover, this promotes pullout failure mode versus interfacial failure mode. These facts can explain increasing in peak load and energy absorption until optimal welding conditions are received.

Mechanical Properties in Expulsion Experienced Welds:
High heat input welding conditions lead to increasing the probability of expulsion occurrence as well as its extent and its associated indentation. As mentioned above, the peak load and failure energy was reduced on expulsion. Reduction of peak load at high welding current and welding time can be related to the reduction in fusion zone size due to increasing heat loss and thinning effect of electrode indentation and associated stress concentration, as reported by Zhang [24] and Han and Indacochea [25]. The surface indentation will change the stress at the weld nugget edge and deep surface indentations are expected to promote premature failure.

Reduction of energy absorption at high welding current can be related to the following reasons:

- **Reduction of weld fusion zone at high welding current:**
  
  As mentioned in Part I [18], the FZ size is reduced on expulsion due to high amount of heat dissipation associated with molten metal ejection from nugget inside.

- **Increasing electrode indentation at high welding current:**
  
  As mentioned in Part I [18], electrode indentation depth is increased by increasing the welding current. Electrode indentation, which can affect mechanical properties of the spot welds, depends on electrode pressure and temperature of electrode/sheet interface. Increasing heat input increases the temperature of electrode/sheet interface, which in turn increases the degree of plastic deformation that can occur in the sheet surface under electrode pressure. Spot welds with expulsion exhibit severe electrode indentation.
CONCLUSIONS

From this study the following conclusions can be drawn:

- Peak load of spot welds depends on the (i) fusion zone size, (ii) electrode indentation, (iii) failure mode and (iv) mechanical strength of the failure location. Energy absorption of spot welds is governed by the factors governing the peak load and ductility of the failure location.
- Generally, increasing welding current increases the peak load and energy absorption primarily due to increasing the overall bond area caused by FZ size enlargement and as a consequence of the transition in failure mode from interfacial to pullout.
- Excessive welding heat input, where expulsion occurs, the peak load and energy absorption capability significantly reduce. Significant reduction of failure energy can be attributed to the reduction of weld fusion zone at high welding current, increasing electrode indentation at high welding current, change in pullout failure location from base metal to weld nugget edge due to severe indentation.
- To maximize the mechanical properties of the spot welds, welding parameters should be adjusted to obtain the spot welds with large fusion zone size, but without excessive electrode indentation and expulsion.

REFERENCES