Analysis of Fracture Mode of Galvanized Low Carbon Steel Resistance Spot Welds

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***Abstract*— Failure mode is a qualitative measure of resistance spot weld (RSW) performance. To ensure reliability of resistance spot welds during vehicle lifetime, process parameters should be adjusted so that the pullout failure mode is guaranteed. In this paper, failure mode of galvanized low carbon steel resistance spot welds is studied under quasi-static tensile-shear test. Results should that increasing welding current alters failure mode from interfacial to pullout failure mode. Considering the failure location and failure mechanism in the tensile-shear test, minimum required fusion zone size to ensure the pullout failure mode was estimated using an analytical model.**

***Keywords*—** Resistance Spot Welding, Galvanized Steel and Failure Mode

I. INTRODUCTION

Resistance spot welding is considered as the dominant process for joining sheet metals in automotive industry.

Typically, there are about 2000–5000 spot welds in a modern vehicle. Simplicity, low cost, high speed (low process time) and automation possibility are among the advantages of this process. Quality and mechanical behavior of spot welds significantly affect durability and crashworthiness of the vehicle [1]. To ensure and maintain structural integrity of finished component under a wide range of operating conditions, e.g. a crash situation, the remotest possibility of producing even one or two defective welds in a critical component needs to be eliminated. These requirements, coupled with uncertainties about weld quality due to the difficulty of applying non-destructive tests to spot welds, are responsible for the practice of making more spot welds than what is actually needed for maintaining structural integrity. A modern vehicle contains 2000 to 5000 spot welds. Around 20% to 30% of these spot welds are due to uncertainty of the quality of spot welds. Significant cost associated with over-welding provides a considerable driving force for optimizing this process [2].

Resistance spot welding is a process of joining two or more metal parts by fusion at discrete spots at the interface of workpieces. Resistance to current flow through the metal workpieces and their interface generates heat; therefore, temperature rises at the interface of the workpieces. When the melting point of the metal is reached, the metal will begin to fuse and a nugget begins to form. The current is then switched off and the nugget is cooled down to solidify under pressure [3-4].

Generally, the resistance spot weld (RSW) failure occurs in two modes: interfacial and pullout. In the interfacial mode, failure occurs via crack propagation through fusion zone; while, in the pullout mode, failure occurs via complete (or partial) nugget withdrawal from one sheet [5-8]. 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. 1.

Spot welds that fail in nugget pullout mode provide higher peak loads and energy absorption levels than those which fail in interfacial failure mode. To ensure the reliability of the spot welds during vehicle lifetime, process parameters should be adjusted so that pullout failure mode is guaranteed [9-14].

In this paper the effect of fusion zone size on the failure mode low carbon galvanized steel is investigated. Minimum fusion zone size required to ensure pullout failure mode is estimated using an analytical mode.

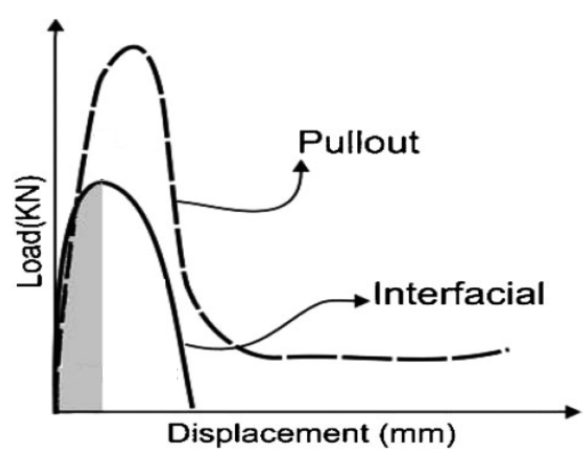


Fig. 1. Load displacement curve for both failure modes

II. EXPERIMENTAL PROCEDURE

A1.1 mm thick galvanized low carbon steel sheet were used as the base metal, in this research. The chemical composition of galvanized low carbon steel is given in Table 1. 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 6-mm face diameter.

In all of the experiments, electrode pressure and squeeze time were kept constant at 4 bar and 45 cycles, respectively. In fixed welding time of 10 cycles, welding current was changed from 10 kA to 12.5 kA. Moreover, in fixed welding current of 11.5 kA, welding time was changed from 8 to 14 cycles.

The static tensile-shear test samples were prepared according to ANSI/AWS/SAE/D8.9-97 standard [15]. Fig.1 shows the sample dimensions. Tensile-shear tests were performed at a cross head of 2 mm/min with an Instron universal testing machine. Peak was extracted from the load-displacement curve. Failure mode was determined from the failed samples.

For metallographic observation, samples were cut along the center of the spot weld nugget in the direction of the width of sample. Subsequently, standard metallographic procedure was applied for microstructural as well as macrostructural investigations. Optical microscopy was used to examine the microstructures and to measure physical weld attributes. After complete separation in the tensile-shear test, cross section of the samples was examined with optical microscope and failure location was determined. Microhardness test was used to determine the hardness profile in horizontal directions (20μm away from weld centerline), using a 100g load on a Shimadzu microhardness tester.

Samples for metallographic examination were prepared using standard metallography procedure. Optical microscopy was used to examine the microstructures of the joints. Fusion zone size of the spot welds was measured using optical microscope. Microhardness test was used to determine the hardness profile of the joints, using a 100g load on a Shimadzu microhardness tester. The microhardness traverses were performed on a diagonal covering microstructural zones in both sheets. The indentations were spaced 0.3 mm apart.

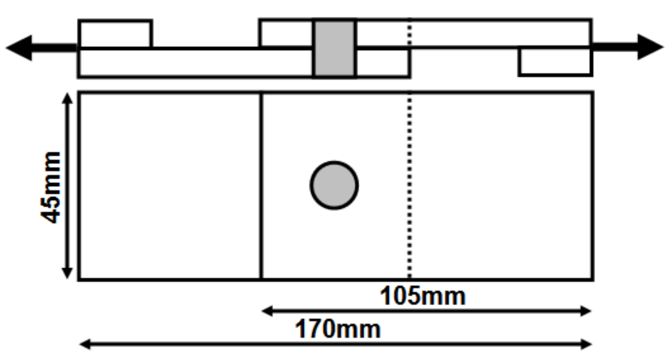


Fig. 2. Sample dimensions for tensile-shear test

III. RESULTS AND DISCUSSION

A. *Microstructure and Hardness Profile*

Fig. 3 shows a typical macrostructure of a galvanized low carbon steel resistance spot weld. As can be seen, the joint region consists of three distinct structural zones:

i) Fusion Zone (FZ) or weld nugget which is melted during welding process and is resolidified showing a cast structure. 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).

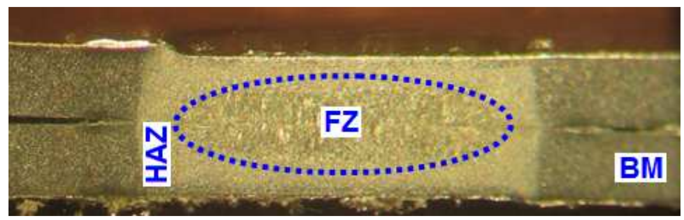


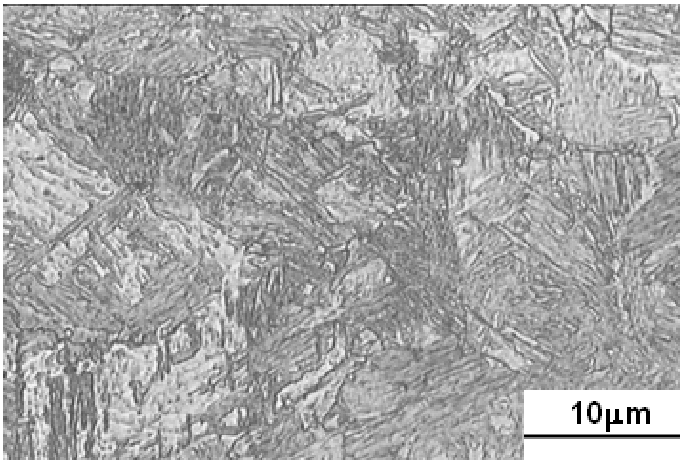
Fig. 3. A typical macrostructure of low carbon steel resistance spot weld

Fig. 3(a) shows the microstructures of FZ which is mainly consisted of martensite. Despite the low carbon content of the base metal, martensite phase was formed due to high cooling rate of RSW process. Weld fusion zone microstructure of low carbon steel RSWs depends on chemical composition of the sheet and cooling rate. Gould et al. [16] proposed a simple analytical model predicting cooling rate during resistance spot welding. According to this model, cooling rate for 1.1 mm thickness is about 8000 Ks^{-1}. Presence of water cooled copper electrodes and their quenching effect as well as short welding cycle can explain high cooling rates of RSW process. For steels, the required critical cooling rate to achieve martensite in the microstructure can be estimated using the following equation [17]:

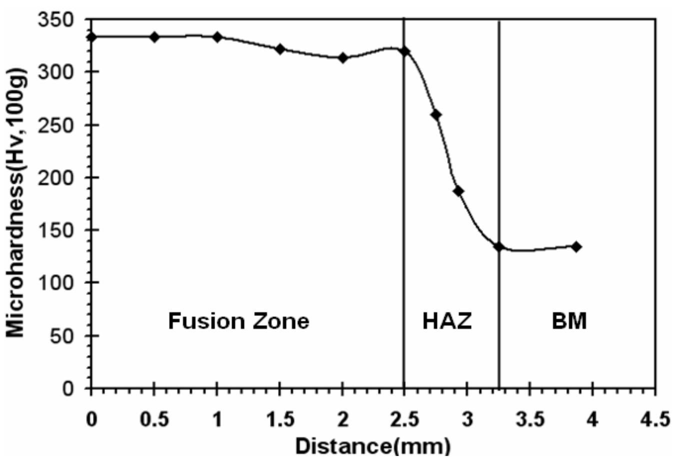
$$\begin{aligned}\text{Log}\, v = 7.42 - 3.13\,C - 0.71\,Mn \\ - 0.37\,Ni - 0.34\,Cr - 0.45\,Mo\end{aligned} \quad (1)$$

Where, v is the critical cooling rate in Kh^{-1}. For the investigated steel, the critical cooling rate is about 2375 Ks^{-1}. Since the cooling rate exceeds the calculated critical value; therefore, it is expected that the fusion zone microstructure consists of mainly martensite, as it is observed.

Fig. 4(b) shows a typical spot weld hardness profile consisting of three zones: weld nugget, HAZ and base metal. Weld nugget hardness is about 2.4 times the value of base metal, due to martensite formation in this zone. Weld nugget hardness is almost constant, which shows that although cooling rate is not constant throughout the weld nugget, it is fast enough to create a relatively uniform microstructure in this zone. Hardness variation in HAZ is almost linear. HAZ severe microstructure gradient is due to weld cycle thermal gradient which in turn causes high changes in hardness values.



(a)



(b)

Fig. 4. (a) Microstructure of FZ, (b) a typical hardness profile

B. Failure Mode

Two distinct failure modes were observed during the static tensile-shear test: interfacial fracture and nugget pullout, as shown in Fig. 5 (a) and Fig. (b).

It is well known that FZ size is the key physical weld attribute controlling the failure mode and mechanical properties of RSWs [9-11]. Effect of welding current on the FZ size is shown in Fig.6a. Fig.6b shows the effect of FZ size on the peak load. FZ size enhanced as the welding current increases due to higher heat generation at sheet/sheet interface. According to Fig. 6 (a) and Fig. (b), the failure mode was changed from IF to PF by increasing the welding current and FZ size. In order to avoid IF mode during tensile-shear test a minimum welding current of 9.5 kA should be used. 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 tend to fail in IF mode [9-11]. Failure of the spot welds can be considered as a competitive process, i.e. failure occurs in a mode which needs less force. During tensile-shear test, the shear stress at the sheet/sheet interface is the driving force for the interfacial mode, and the tensile stress at the nugget circumference is the driving force for the pullout failure mode [9-11]. Each driving force has a critical value and the failure occurs in a mode which its driving force reaches its critical value, sooner. The FZ size is the governing parameter determining stress distribution. For small weld nuggets, the shear stress reaches its critical value before the tensile stress causes necking; thus, failure tends to occur under interfacial mode. Therefore, there is a critical weld FZ size beyond which, the pullout failure mode is expected.

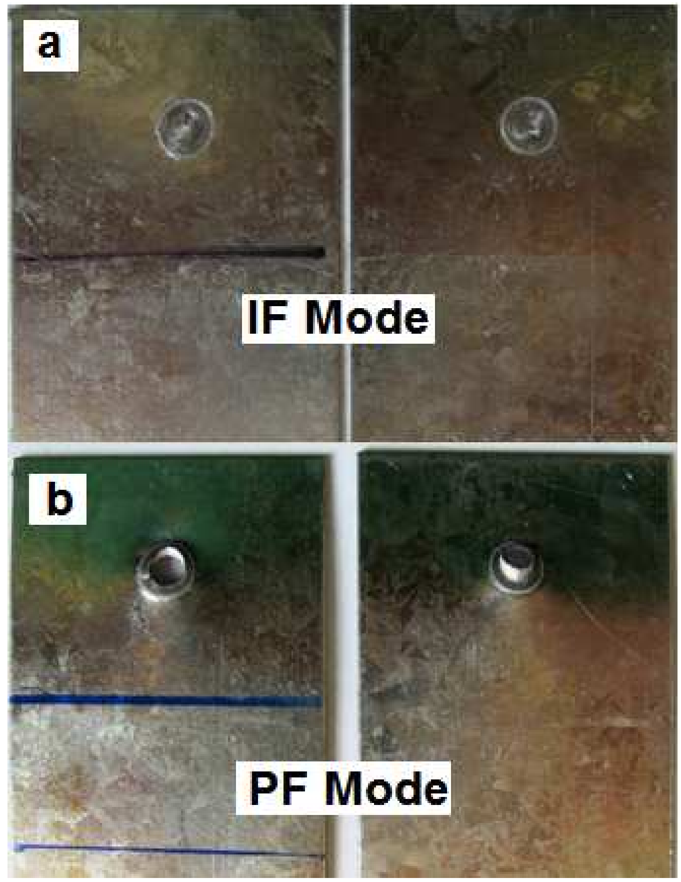
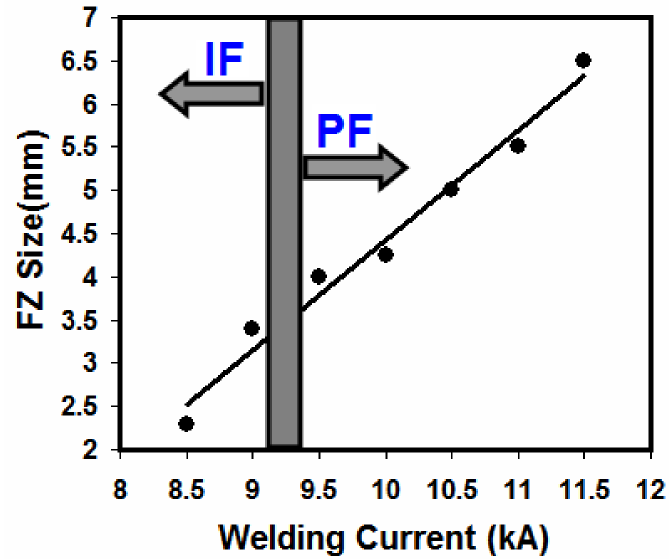


Fig. 5. Observed spot weld failure modes: (a) interfacial, (b) nugget pullout

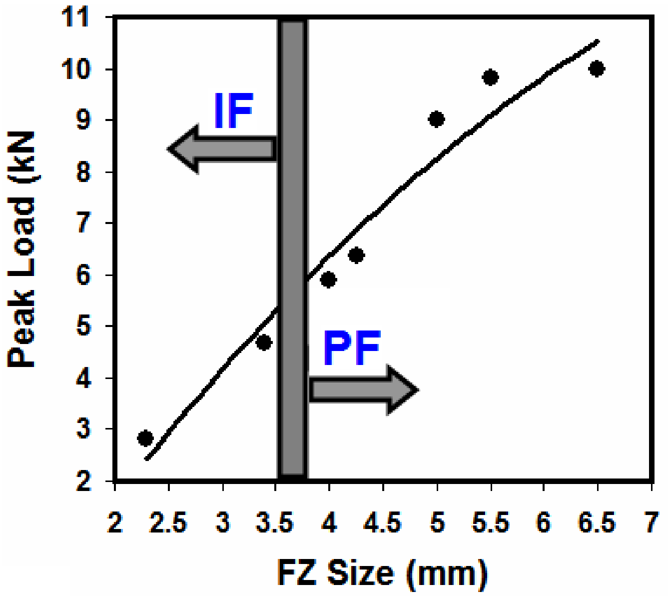
C. Critical Fusion Size

In this section, a simple analytical model is proposed to predict joint failure mode during the tensile-shear testing of austenitic stainless 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:



(a)



(b)

Fig. 6. (a) Effect of welding current on FZ size, (b) effect of FZ size on the peak load

$$P_{IF} = (\frac{\pi d^2}{4})\tau_{FZ} \qquad (2)$$

Where: τ_{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.

$$P_{PF} = \pi d t \sigma_{PFL} \qquad (3)$$

Where: σ_{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_{Cr}) can be defined which determines which one of the failure modes happens. Spot welds with $d<d_{Cr}$ tend to fail via interfacial failure and welds with $d>d_{Cr}$ tend to fail via nugget pullout failure mode.

Therefore, to obtain critical nugget diameter, d_{Cr}, equations (2) and (3) are intersected resulting in equation (4):

$$d_{Cr} = 4t\frac{(\sigma_{UTS})_{FL}}{\tau_{FZ}} \qquad (4)$$

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. On that account, equation 4 can be rewritten as follows:

$$d_{Cr} = 4t\frac{H_{FL}}{f \times H_{FZ}} \qquad (5)$$

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_{Cr}).

Fig. 5 shows the cross section of a sample failed through the pullout failure mode during the tensile-shear test. The necking due to plastic deformation is evident in the one leg. The failure of the spot weld appears to be initiated near the middle of the nugget circumference, and then propagated by necking/shear along the nugget circumference until the upper sheet is torn off. The observed mechanism is in agreement with that of mentioned by Zuniga and Sheppard [18]. As can be seen from Fig.7, the pullout failure location is at the base metal (BM). This can be attributed to the low hardness of the base metal rather than HAZ and fusion zone which provide a preferential location for necking during the tensile-shear test.

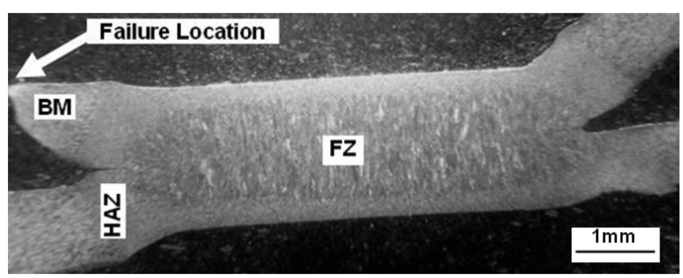


Fig. 7. Cross section of fracture surfaces of spot welds in tensile-shear test: One leg of the lower sheet and one leg of the upper are subjected to tensile stress.

In the case of low carbon galvanized steel, average FZ hardness is approximately 335 HV and hardness of the base metal is about 140HV. Therefore, the hardness ratio of FZ to failure location is about 2.4. By substituting these values in equation 5, critical fusion zone size is calculated to be 3.7 mm.

Fig. 6b shows that this value separates the interfacial and nugget pullout failure modes.

IV. CONCLUSION

1) Increasing welding current leads to alter failure mode from interfacial failure mode to pullout mode. A minimum FZ size of 4.1 mm is required to ensure pullout failure mode during the tensile-shear test.
2) The proposed analytical model successfully predicts the critical weld fusion zone size for galvanized low carbon 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.
3) Fusion zone size proved to be the most important controlling factor of the spot weld peak load due to the increasing of the overall bond area caused by increasing the FZ size and also as a consequence of the transition in the failure mode from interfacial to pullout.

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