Effect of Welding Current on the Mechanical Response of Resistance Spot Welds of Unequal Thickness Steel Sheets in Tensile-Shear Loading Condition

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Abstract— **Resistance spot welding is the dominant welding process in sheet metal joining particularly in automotive industry. Despite various applications of dissimilar thickness resistance spot welding in car body, reports in the literature dealing with their mechanical behavior are limited. This paper investigates the effect of welding current, as the main resistance spot welding process parameters, on the weld nugget attributes and mechanical performance of resistance spot welds of 1.25 to 2.5 mm thick low carbon steel sheets. The mechanical properties of the welds were described in terms of peak load and failure energy. Results showed that in contrast to spot welding of sheets with similar thickness, a Pear- like shape of the weld nugget was formed due to heat unbalance resulted from difference in bulk resistively of the sheets. In RSW, heat balance can be defined as a condition in which the fusion zones in both pieces being joined undergo approximately the same degree It was concluded that there is a direct correlation between peak load (and energy absorption) and (fusion zone size × weld penetration).**

Keywords— Resistance Spot Welding, Unequal Sheets, Peak Load and Failure Energy

I. INTRODUCTION

Resistance welding is that area of welding where heat is generated by the resistance of the parts being welded to the flow of a localized electric current. Pressure is applied to ensure adequate contact between the parts being welded. The welding current and force are applied to the workpiece via copper alloy electrodes, which are shaped to provide the required current density and pressure at the point of welding [1]. Spot welding is the most widely used variant of the resistance welding processes. It involves the coordinated application of electric current and mechanical pressure of the correct magnitudes and format.

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 [2-4].

There are generally three indexes for quality control of resistance spot welds:

i) Fusion Zone Size (FZS)

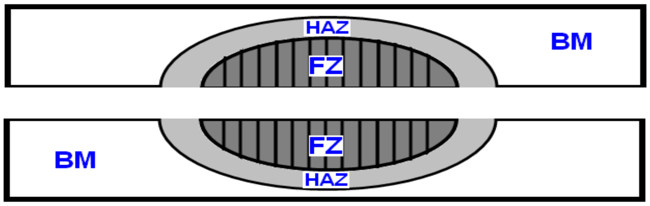
FZS which is defined as the width of the weld nugget at the sheet/sheet interface in the longitudinal direction is the most important factors in determining quality of spot welds.

ii) Weld Mechanical Performance

Spot weld mechanical performance is generally considered under static/quasi-static and fatigue loading condition. The tensile-shear test is the most widely used test for evaluating the spot weld mechanical behaviors in static condition [5]. Peak load, obtained from the tensile-shear load-displacement curve, is often used to describe spot welds mechanical behaviors. In addition to peak load, failure energy can be used to better describe the spot weld mechanical behaviors. Failure energy is a measure of weld energy absorption capability, and its higher value demonstrates the increase in weld performance reliability against impact loads such as accidents [6-8].

iii) Failure Mode

Failure mode is the manner which spot weld fails. Generally, the resistance spot weld (RSW) failure occurs in two modes: interfacial and pullout [9-10]. Fig.1 shows typical fracture modes of spot welds. In the interfacial failure (IF) mode, failure occurs via crack propagation through fusion zone; while, in the pullout failure (PF) mode, failure occurs via nugget withdrawal from one sheet. Spot weld failure mode is a qualitative measure of the weld quality. Failure mode can significantly affect 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. 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 same weld would have been able to transmit a high level of force, thus cause severe plastic deformation in its adjacent components, and increased strain energy dissipation in crash conditions [11]. Therefore, it is needed to adjust welding parameters so that the pullout failure mode is guaranteed.



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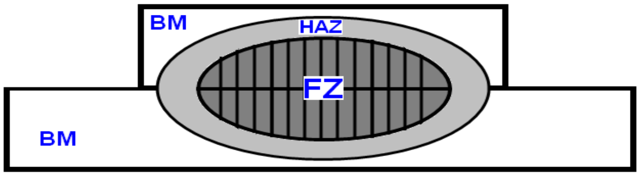

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Fig.1: Schematic representation of main failure modes of spot welds: (a) interfacial and (b) pull-out

The majority of investigations on spot welding have been carried out on welding two sheets with equal thickness. In practice, this is typical of many applications in general engineering, domestic appliances and building industries. However, in automotive body in-white applications, the majority of welds are between two dissimilar thicknesses [1], [5]. Despite various applications of dissimilar thickness RSWs, reports in the literature dealing with their mechanical behavior are limited. Therefore, this paper aimed at investigating the effect of welding current, as the main resistance spot welding process parameters, on the weld nugget attributes and mechanical performance.

II. EXPERIMENTAL PROCEDURE

The 1.25 mm and 2.5 mm thick uncoated low carbon steel of the type used in the automotive industry were used in the investigation. The chemical composition of the steels is given in Table I. The microstructure of both steel sheets exhibits a ferritic structure.

TABLE I
CHEMICAL COMPOSITION OF TEST MATERIALS (WT %)

Base metal	C	Mn	Si	S	P
1.25 mm	0.08	0.21	0.0.1	0.007	0.05
2.5 mm	0.05	0.20	0.05	0.005	0.01

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-deg truncated cone RWMA Class 2 electrode with 8-mm face diameter. In all experiments, welding time, electrode force and holding time were kept constant at 0.2s, 4.2 kN and 0.6 s, respectively. Welding urent was varied from 7 to 13.5 kA.

Fig. 2 shows the tensile-shear sample dimensions. Static tensile-shear tests were performed at a cross head of 2 mm/min with an Instron universal testing machine. The peak load and the failure energy were extracted from the load displacement curve. The failure energy was calculated as the area under the load displacement curve up to the peak load. It should be

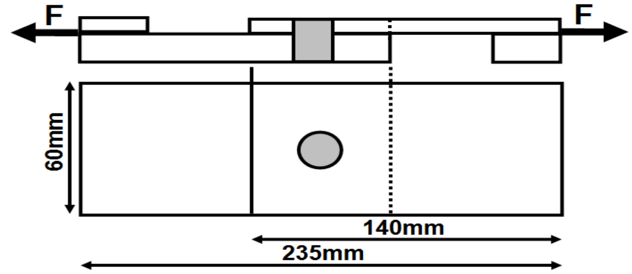


Fig. 2: Tensile-shear specimen dimensions

noted that the total energy when the specimen finally fails is not quite relevant to a weld's performance but it reflects more on the influence of the specimen rather than the spot weld [5]. Failure mode was determined from the failed samples. Samples for metallographic examination were prepared using standard metallography procedure. Optical microscopy was used to examine the microstructures and to measure the physical weld attributes (i.e., weld nugget size and weld penetration).Before and after complete separation in the tensile-shear test, failure location of the samples was examined by optical microscope.

III. RESULTS AND DISCUSSION

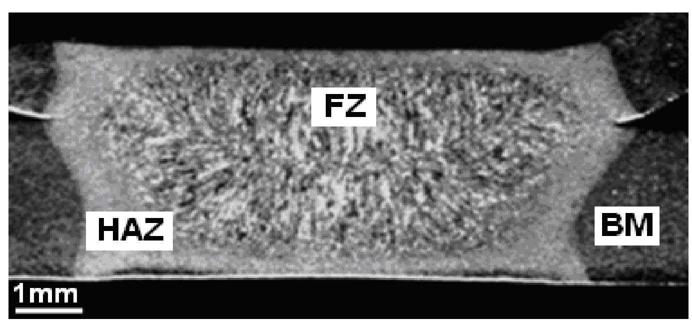
A. *Weld Macrostructure*

Fig. 3(a) shows a typical macrostructure of the spot welds between two dissimilar thickness low carbon steel. As can be seen, joint region consists of three different microstrutural regions, namely:

i) Fusion Zone (FZ) 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)



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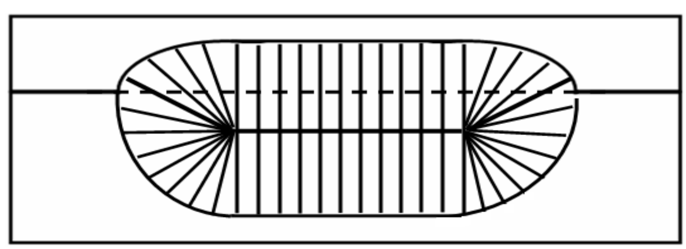


(b)

Fig. 3: A typical macrostructure of dissimilar thickness RSW

Fig. 3(b) shows a schematic representation of weld nugget in dissimilar thickness resistance spot welds. As can be seen in Fig. 3(a) and Fig. 3(b), Pear- like shape of the weld nugget (heat unbalance) is one of the interesting features of the weld nugget. In RSW, heat balance can be defined as a condition in which the fusion zones in both pieces being joined undergo approximately the same degree of heating and applied pressure. It describes the ideal situation when a symmetric weld (with equal depth of nugget penetration) is made. Heat balance is influenced by the relative thermal and electrical conductivities of the materials to be joined, the geometry of the weldment, and the geometry of the electrodes [12]. In the case of dissimilar thickness, bulk resistance of thicker sheet is lager than that of the thinner sheet. This leads to an asymmetric weld nugget (i. e. penetration of the weld nugget into the thicker sheet is larger than that of the thinner sheet). This can be overcome by using electrodes of two different diameters or by inserting a high-resistivity tip in one electrode. The smaller electrode or the one with high-resistivity insert should be placed against the thinner of the two sheets.

B. Effect of Welding current on the Weld Attributes

Fig. 4 shows the effect of welding current on the FZ size (i. e the size of weld nugget at sheet/sheet interface). As can be seen, generally, the FZ size is increased as the welding current increases. 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. Generated heat during resistance spot welding can be expressed as follows:

$$Q = R\, I_W^{\,2}\, t_W \tag{3}$$

Where, Q, R, Iw and tw are generated heat, electrical resistance, welding current and welding time, respectively. Therefore, increasing welding current increases the FZ size, however, the as can be seen in Fig.4, the rate of weld nugget growth is not constant over the welding current range. As can be seen, FZ size versus welding current curve can be divided in four regions:

Region I (Incubation period)

In this region, fusion does not occur. As can be seen a minimum welding current of 8.5 kA is needed to formation fusion zone.

Region II (Rapid weld growth period)

As can be seen, the weld nugget growth rate in 8.5 to 10.5 kA welding current is high.

Region III (Slow weld nugget growth)

As can be seen, in the range of 10.5 to 12.5 kA of welding current, the weld nugget growth **be**comes slower. This can be related to the reduction of dynamic resistance of the weld nugget by increasing welding current.

Region IV (Expulsion)

As can be seen, increasing beyond 12.5 kA leads to reduction in FZ size due to expulsion (i.e., molten metal ejection from the weld nugget).

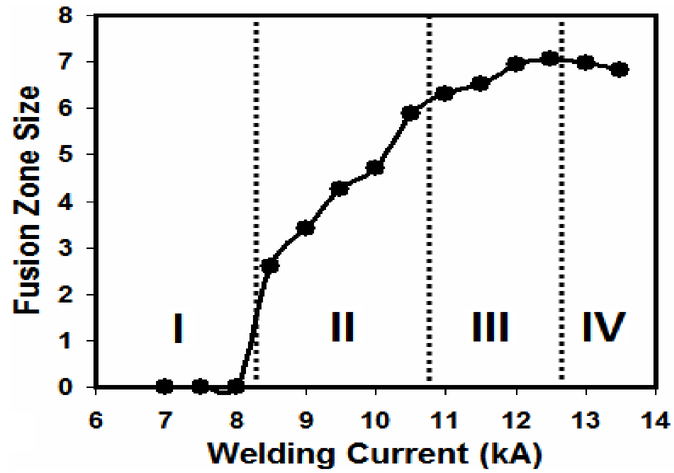


Fig. 4: Effect of welding current on the FZ size

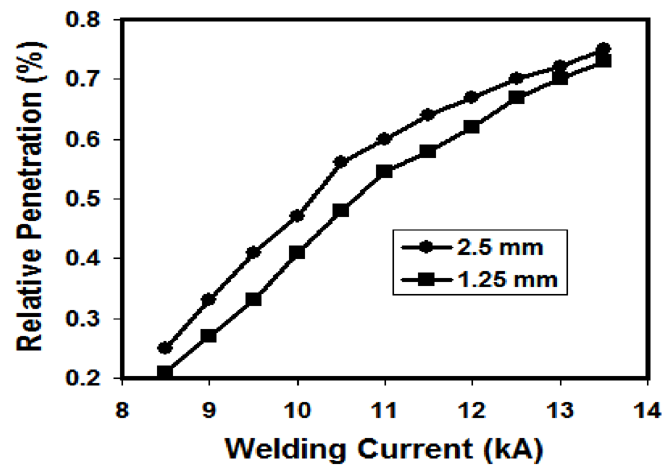


Fig. 5: Effect of welding current on the weld penetration

Fig. 5 shows the variation of the relative fusion penetration (measured as the penetration depth in each sheet divided by the sheet thickness) with welding time for two sides. As can be seen, fusion penetration percent in the thicker sheet is larger than that of the thinner sheet. This can be related to the higher bulk electrical resistance of the thicker sheet compared to the thinner sheet.

C. Tensile-shear Mechanical Performance

Fig. 6(a) shows the effect of welding current on the peak load. As can be seen increasing welding current leads to increasing peak load. This is due to increasing FZ size and weld penetration. Fig. 6(b) shows the effect of (FZ size × weld penetration) on the peak load. As can be seen, there is a direct correlation between FZ size (D) × weld penetration (P). To establish a relationship between weld attributes and peak load, the following relation was developed mathematical regression:

$$\textit{Peak Load} = 0.6482\, PD + 3.2467$$

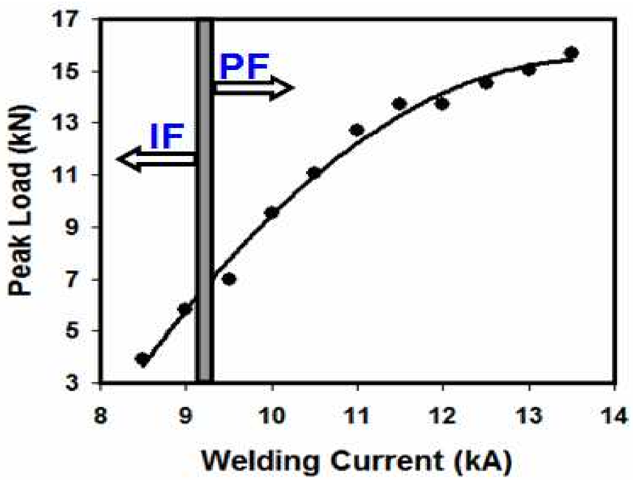
Fig. 7(a) shows the effect of welding current on the failure energy. As can be seen increasing welding current leads to increasing failure energy. This is due to increasing FZ size and weld penetration. Fig. 7(b) shows the effect of (FZ size × weld penetration) on the failure energy. As can be seen, there is a direct correlation between FZ size (D) × weld penetration (P). To establish a relationship between weld attributes and peak load, the following relation was developed mathematical regression:

$$Failure\ Energy = 11.107\ PD\text{-}24.976$$

As can be seen, increasing welding current beyond 9 kA alters failure mode from interfacial to pullout mode. This is due to increasing FZ size. Increasing FZ size, increases the weld nugget resistance against interfacial (i.e., shear) failure. It is well known that there is a critical FZ size above which the pullout failure mode is guaranteed. As can be seen in Fig. 7, the failure energy of the spot welds failed in IF mode is much lower than that of failed in PF mode due to little plastic deformation associated with interfacial failure process.

IV. CONCLUSION

1) In contrast to spot welding of sheets with similar thickness, a Pear- like shape of the weld nugget was formed due to heat unbalance resulted from difference in bulk resistively of the sheets.
2) Increasing welding current beyond 9 kA alters the failure mode from interfacial to pullout mode.
3) Weld nugget size and weld fusion penetration are the main controlling factors for spot weld quality in terms of peak load and energy absorption.
4) Direct correlation between peak load (and energy absorption) and (FZ size × weld penetration) were found.



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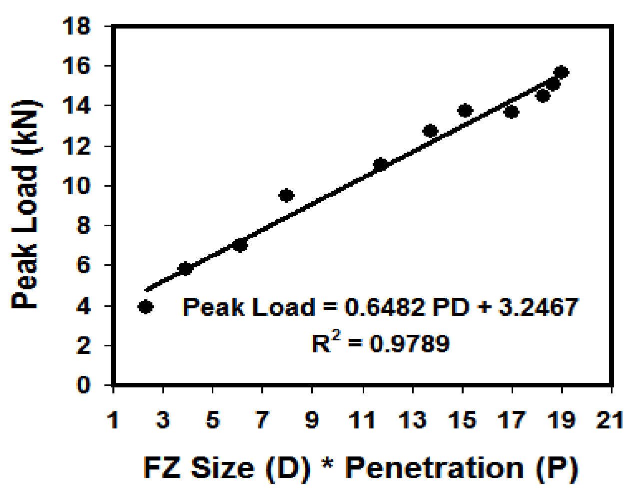

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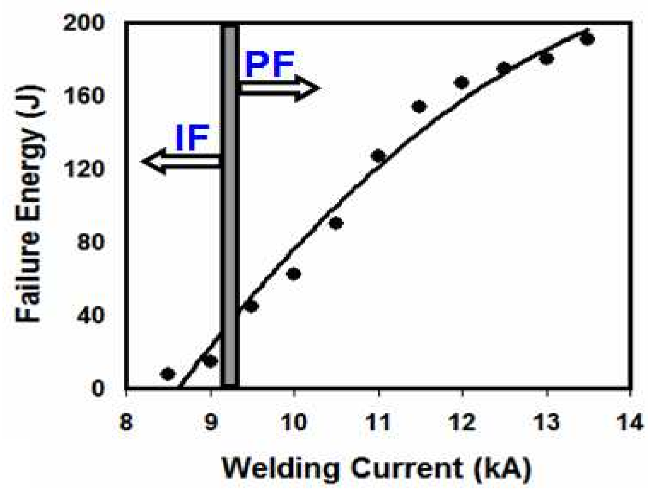
Fig. 6: (a) Effect of welding current on the peak load (b) effect of (FZ size × weld penetration) on the peak load



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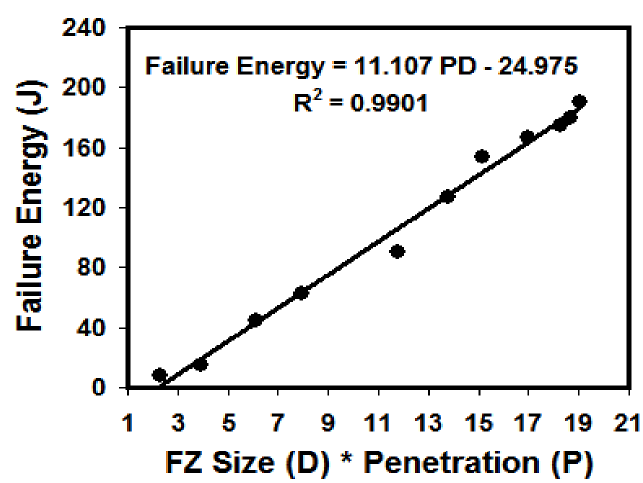

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Fig. 7: (a) Effect of welding current on the failure energy (b) effect of (FZ size × weld penetration) on the failure energy

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