

## FRACTURE BEHAVIOR OF DISSIMILAR RESISTANCE SPOT WELDED OVERLAP JOINT

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### ABSTRACT

*The resistance spot welding process is also used for the welding of dissimilar materials. A dissimilar joint is formed by two sheets: a 1.0 mm thick sheet of low-alloy carbon steel and a 1.5 mm thick sheet of aluminium alloy 6061 T6. In this study, the effects of welding current and nugget diameter are investigated. Welding times and welding force are kept constant. Tensile shear tests were applied in order to determine the strength parameters of the dissimilar joint. The experimental results show that an increase in the welding current increases the tensile shear stress and the weld nugget diameter. This study used a fracture mechanics-based approach, to investigate the influence of resistance spot welding parameters on the critical stress intensity factor. The results show that the critical stress intensity factor is maximal for a welding current equal to 16 kA. Also, the maximum tensile shear strength is achieved at an 8 mm nugget diameter, which is influenced by an increase in the welding current.*

**KEYWORDS:** resistance spot welding, dissimilar lap joint, welding current, critical stress intensity factor, aluminium-alloy/low carbon steel

### 1. Introduction

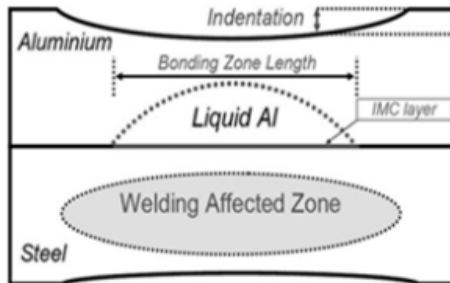
Resistance spot welding (RSW) represents the major welding process used in various manufacturing industries, especially in automobile truck cabin manufacturing, rail vehicles, motorcycles, and home appliances, such as refrigerators. For example, there are 3000 to 12000 spot welds in an automobile [1]. The majority of research investigations in spot welding have been carried out on the joining of homogeneous materials [2, 3]. Currently, research in different industries is directed towards the reduction of CO<sub>2</sub> emissions. Hence, the combination of heterogeneous materials is necessary in order to reduce the weight of structures and, consequently, CO<sub>2</sub> emissions [4]. Engineers are increasingly faced with joining different material types where they are looking for joints ensuring good mechanical strength and corrosion resistance, and ensuring a good sealing function [5]. Also, for a dissimilar Al/steel joint welded using direct RSW, as shown in Figure 1,

different metallurgical phenomena occur [6]. The mechanical properties of Al/steel RSW depend on several factors controlling the quality of the joints. The factors controlling the mechanical properties can be summarized as follows: bonding zone length, the thickness of the IMC layer, electrode indentation in the Al sheet, and defects at the joint interface [7-9].

RSW of dissimilar materials, specifically high-strength galvanized steel and Aluminium alloy, was investigated by Zhang *et al.* [10]. Qui *et al.* [11] have studied the interfacial characterization of the joint between mild steel and an aluminium alloy welded by resistance spot welding with an applied cover plate technique. It is noticed from this study that there is an improvement in mechanical properties. All the cited researches are oriented toward studying mechanical properties under different welding parameters.

The study conducted by Zhang and Sun [12] investigates the mechanical behavior of RSW joints between two dissimilar material types, namely 301L austenitic stainless steel and 6063-T6 aluminium

alloy, as well as the effects of welding parameters. The results show an increase in nugget diameter and tensile shear load with the increase in welding current and welding time.



**Fig. 1.** Schematic of the macrostructure of dissimilar resistance spot welds between aluminium and steel, along with details of the interfacial reaction zone [6]

In the study conducted by Xu *et al.* [13], the resistance spot welding process was performed to join aluminium alloy and low-alloy carbon steel plates. The nugget diameters, indentation rates, microstructure, and tensile-shear strength of the RSW joints were investigated. The nugget diameters and the indentation rates of the RSW joints increased when increasing either the welding current or the welding time, and decreased when increasing the electrode pressure.

The research conducted by Ramdani *et al.* [14] reveals that welding parameters and nugget diameter are important factors that determine the load-bearing capacity of the overloaded RSW joint and its resistance to fracture.

Recently, several researches have been oriented toward fracture or fatigue behavior that depends on the stress intensity factor. Pook's resistance spot welding stress analysis refers to early fracture mechanics work by L.P. Pook, which applied stress intensity factors to predict the fatigue life of spot-welded joints [15]. His approach aimed to improve the scatter of fatigue data by analysing fatigue crack growth in terms of stress intensity factors rather than just load, though his method was limited to small-scale yielding and low applied loads [16]. More recent research continues to build on this foundation, using more advanced finite element analysis (FEA) to determine stress intensities and fatigue life [17], with some studies verifying results against Pook's work or developing alternative parameters, such as the fatigue evaluation parameter. Based on a stress analysis around the spot weld in lap joints and coach peel

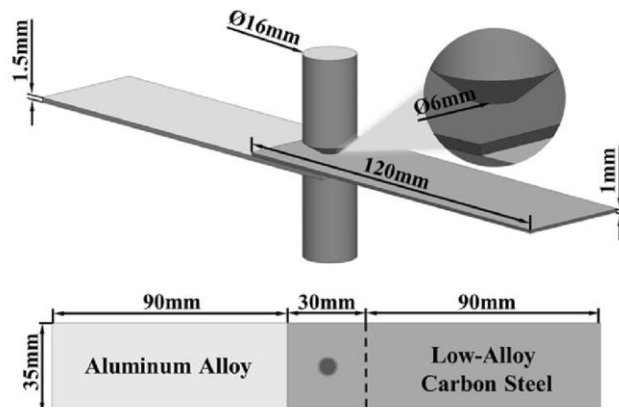
joints of Pook's work, Zhang [18] has determined the stress intensity at the spot weld for overlap joints and coach peel joints, with the assumption that the nugget has a circular shape.

Radja and Zhang [19] have proposed simplified formulae for stress intensity factors to evaluate the fracture toughness in spot welds. Also, Zhang [20] has proposed analytically an approximate stress intensity factor to use in optimizing the fatigue-resistant spot weld for different specimen configurations. Benchadli *et al.* [21] have studied the effect of resistance spot welding parameters on the stress intensity factor for a homogeneous joint with 316L stainless steel using Zhang's approach, where the welding current presents the dominant parameter. Recently, Fakhri *et al.* [23] have conducted an experimental and numerical investigation of the mechanical properties and stress intensity factor of a dissimilar spot weld joint (Al-Cu).

Based on the literature, the evaluation of the critical stress intensity factor is oriented principally toward homogeneous joints, especially for steel materials, and there is limited research for aluminium alloys. The association of two different materials with different densities contributes to the formation of an intermetallic compound after welding between the Al-alloy and steel. In this regard, great attention must be paid to the fracture behavior at the resistance weld point especially the estimation of the critical stress intensity factor. This research aims to evaluate the critical stress intensity factors for a dissimilar lap joint with two different materials (aluminium alloy 6061 T6 and low-alloy carbon steel) based on Zhang's approach [18, 20] under the influence of welding current and nugget diameter for a fixed welding time and electrode force.

## 2. Experimental data base

The experimental database was derived from the published work initiated by Xu *et al.* [13]. The experimental results are based on tensile shear tests of dissimilar spot-welded joints composed of low-alloy carbon steel and 6061 T6 Al-alloy. The welding current varies from 11 to 18 kA, the welding time and electrode force are fixed to 250 ms and 3 kN, respectively. The geometry of the resistance spot welding joint is given in (Figure 2). The experimental results for the nugget diameter and maximal shear force as a function of the welding current are given in Table 1.



**Fig. 2.** Dimensions of a dissimilar RSW sample for tensile shear tests [13]

**Table 1.** Nugget diameter and maximum tensile shear force as a function of the welding current [13]

| I (kA) | D (mm) | F (N)   |
|--------|--------|---------|
| 11     | 4.13   | 995.73  |
| 12     | 5.22   | 1113.25 |
| 13     | 5.34   | 1294.87 |
| 14     | 6.99   | 1588.68 |
| 15     | 7.68   | 1807.69 |
| 16     | 7.99   | 2026.71 |
| 17     | 8.17   | 1674.15 |
| 18     | 8.18   | 1485.00 |

$$K_I = \frac{F \cdot \sqrt{3}}{2\pi \cdot D \cdot \sqrt{t}} \quad (1)$$

$$K_{II} = \frac{F}{\pi \cdot D \cdot \sqrt{t}} \quad (2)$$

The maximum KIII at the nugget edge side facing the vertex at point B (Fig. 3) for tensile-shear spot welds is given by equation 3:

$$K_{III} = \frac{F \cdot \sqrt{2}}{\pi \cdot D \cdot \sqrt{t}} \quad (3)$$

The equivalent stress intensity factor is given by equation 4:

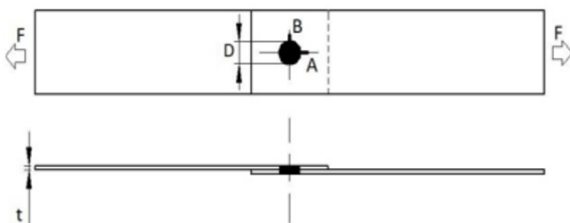
$$K_{eq} = \frac{F \cdot \sqrt{19}}{2 \cdot \pi \cdot D \cdot \sqrt{t}} \quad (4)$$

where D is the diameter of the nugget (mm), “t” is the thickness of the plate (mm), and F is the maximum applied force in tensile shear resistance spot welding.

### 3. Results & discussion

#### 3.1. Critical stress intensity factor model

In this study, a tensile shear overlap joint is used (Figure 3). The significant stress-inducing variables at the front-facing vertex parallel to the loaded direction (at point A in Figure 3), KI and KII, occur concurrently and can be determined by Zhang’s method [19, 21]. Also, other analytical and numerical solutions for the stress intensity factor have been determined and are suitable for a novel application to dissimilar resistance spot welding [22].



**Fig. 3.** Tensile shear of a dissimilar overlap joint

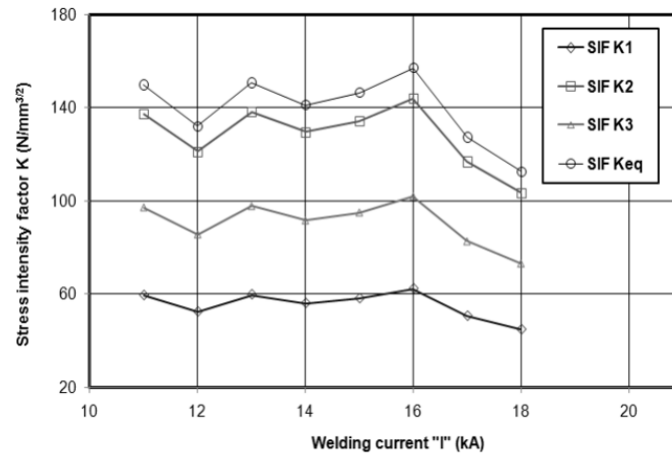
#### 3.2. Effect of welding current on critical stress intensity factor

As exhibited in Figure 4, an increase in the welding current from 11 kA to 15 kA results in a low variation in the equivalent stress intensity factor  $K_{eq}$ , from 149.7 to 146.3 N/mm<sup>3/2</sup>. The maximum stress intensity factor,  $K_{eq}$ , is achieved at a welding current equal to 16 kA with a value of 156.9 N/mm<sup>3/2</sup>. From I = 17 to 18 kA, it is noticed that there is a reduction in the equivalent stress intensity factor, where the minimum value is 112.5 N/mm<sup>3/2</sup> for I = 18 kA; this is attributed to the large nugget diameter. The obtained results show that I = 16 kA is the optimal welding current. This result is confirmed by the published work of Benchadli *et al.* for a 316L

homogeneous joint [21]. The critical stress intensity factors of all modes (KI, KII and KIII) are controlled by the ratio of tensile shear force to nugget diameter: F/D).

Also, the variation of the stress intensity factor in mode II follows the same tendency compared to the equivalent stress intensity factor. The maximum stress intensity factor is identified at a welding

current of  $I = 16$  kA. The critical stress intensity factor in mode II exhibits higher values for all welding currents relative to mode I and mode III. The critical stress intensity factor for mode I shows low values under the variation of welding current compared to modes II and III. The maximum stress intensity factor is about  $62.33 \text{ N/mm}^{3/2}$  for a welding current equal to 16 kA.

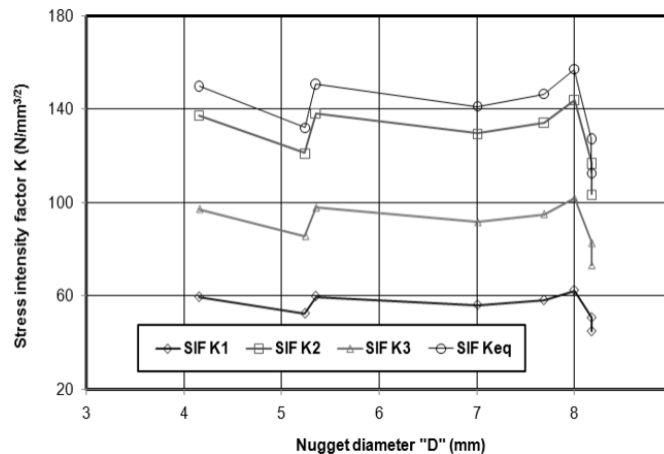


**Fig. 4.** Effect of welding current on the critical stress intensity factor for a dissimilar RSW joint 6061-T6/low-alloy carbon steel

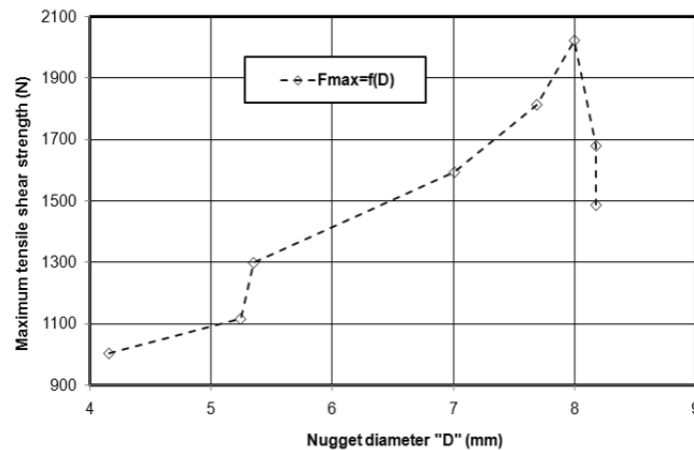
The effect of the nugget diameter as a function of weld current is given in (Figure 5). A low variation of the critical stress intensity factor during the increase in welding current from 11 to 17 kA can be observed. Also, it is noticed that the maximum value for the nugget diameter is equal to 8 mm. Before this value of nugget diameter, a decrease in the critical stress intensity factor is shown for all modes of fracture mechanics at the resistance spot welding points. The intensity coefficient remains the same for both  $K_{eq}$  and KII as the weld zone diameter changes.

This result shows that the fracture of the resistance spot welding point is governed by mode II rather than mode I.

The maximal tensile shear strength as a function of the nugget diameter is given in (Figure 6). An exponential evolution is shown for the increase in nugget diameter between 4.16 mm and 8 mm. The maximum tensile shear strength equal to "2020 N" is obtained at a nugget diameter equal to 8 mm, followed by a decrease to 1485 N at a nugget diameter equal to 8.18 mm.



**Fig. 5.** Effect of the nugget diameter on the stress intensity factor of a dissimilar lap joint 6061-T6 / low-alloy carbon steel



**Fig. 6.** Evolution of the maximum tensile shear strength as a function of the nugget diameter

#### 4. Conclusions

The quality of spot weld joints is strongly related to the welding current. The investigation into resistance spot welding joints reveals a complex relationship between the welding current, mechanical properties, and the formation of the nugget, especially in dissimilar resistance spot welding joints. In conclusion, the observed trends highlight the critical importance of selecting an optimal welding current to achieve the desired mechanical properties and fracture parameters in resistance spot welding joints. Results reveal a direct relationship between the welding current and the nugget diameter. It is crucial to comprehend the relationship between the welding current and fracture toughness (critical stress intensity factor). The second mode of fracture, KII, dominates the fracture process in resistance spot welding compared to fracture modes I and III. The maximum equivalent critical stress intensity factor ( $K_{eq}$ ) is obtained at a welding current equal to 16 kA. Also, the relationship between the equivalent critical stress intensity factor and the nugget diameter shows that the maximum  $K_{eq}$  is achieved at the nugget diameter corresponding to  $I = 16$  kA. The dissimilar joint (aluminium alloy/low carbon steel) exhibits low values of the critical stress intensity factor compared to stainless steel or low carbon steel homogeneous joints.

#### Nomenclature

I - Welding current (kA)  
D - Nugget diameter (mm)  
F - Maximum tensile shear (N)  
T - Thickness of the RSW joint (mm)  
KI - Stress intensity factor in mode I ( $N/mm^{3/2}$ )  
KII - Stress intensity factor in mode II ( $N/mm^{3/2}$ )  
KIII - Stress intensity factor in mode III ( $N/mm^{3/2}$ )

$K_{eq}$  - Equivalent stress intensity factor ( $N/mm^{3/2}$ )

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