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MATERIALS CHARACTERIZATION

Mechanical characterization of spot friction stir welded joints in aluminum alloys by combined experimental/numerical approaches
Part I: Micromechanical studies

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ABSTRACT

This paper is part I of a two part paper, which summarizes recent studies carried out to characterize the weld zone mechanical properties in aluminum alloy 6111 spot friction stir welded joints at both the macromechanical and micromechanical levels. In this paper, micromechanical level investigations are reported for joints welded with different processing times. Apart from microstructural studies and microhardness tests, a new approach to characterize the distribution of weld zone modulus using modal vibration tests on micron scale cantilever array specimens with a micro-scanning laser vibrometer and the corresponding finite element simulations has been developed. Microcantilever array samples were designed in such a way that each microcantilever represents one of the weld zones. Microscopic studies reveal a partial metallurgical bond formed in the direction of flow, which is governed by the tool used and Vickers hardness numbers in those regions were found to be considerably lower than those of the base metal. From the analysis of microcantilever arrays, it was concluded that the variation of modulus in the weld zones is minimal and there is no significant reduction in the weld zone modulus when compared to that of the base metal.

1. Introduction

The use of aluminum in the construction of automobiles is on the rise in order to reduce weight and improve fuel efficiency. This raises an important issue on how to join aluminum parts efficiently and economically and also the need to characterize the mechanical properties of welds. There are many methods available to join aluminum: tungsten inert gas (TIG), metal arc welding (MIG) and resistance spot welding (RSW) to name a few. All the above methods require heating/melting of the aluminum alloy base metal. Other methods which do not require melting of aluminum alloy base metal are self piercing riveting (SPR), clinching and bonding with structural adhesives to name a few.

Spot friction stir welding (SFW) also known as friction stir spot welding (FSSW) is a novel variant of the “linear” friction stir welding (FSW) process developed by Mazda Corporation and Kawasaki Heavy Industries in 2003 as a solid state joining technique to join aluminum alloys [1]. FSW, which was invented by The Welding Institute (TWI) in 1991 and SFW are promising joining processes that have shown potential practical applications for welding aluminum alloys in the automotive industry [2]. FSW and SFW have been successfully

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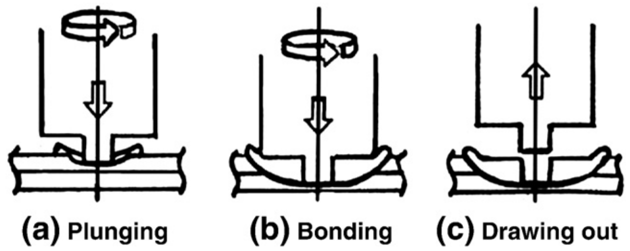

Fig. 1 – Illustrating fixed-pin spot friction weld (SFW) process [3].

used to produce high-quality joints and these methods also make it possible to join high strength aluminum alloys [2,3].

A quantitative comparison of joints made by RSW, SPR and SFW was reported by Briskham et al. [4] on the basis of tensile strength, process time, and cost (equipment and running cost). Aluminum alloy sheets having a wide range of thickness were joined using the above three methods. It was concluded that the lap-shear strength of joints produced by the SFW process were comparable to those produced by RSW or SPR, however, the process time required to join the sheets using SFW increased monotonically with increasing thickness. SFW process advantages are lower power consumption than RSW, and lower running costs. Furthermore, unlike RSW, no weld spatter occurs during the SFW process, resulting in a better work environment. Other merits of the SFW process include long tool life, high productivity and high reliability.

1.1. *Spot Friction Welding Process*

There are two different methods of making joints by the SFW process, one based on the fixed-pin approach [3] and another based on the fixed position approach [5]. The fixed-pin approach is simpler in the equipment and tooling and also has been used to produce joints effectively on thin aluminum alloy 6111-T4 sheets [6–9]. The fixed-pin approach employs a cylindrical tool with a fixed-pin tip centered on one circular face as shown in Fig. 1 (a–c). The fixed-pin tool rotating circumferentially at a pre-determined speed at room temperature is plunged into the upper sheet with a normal force, while a backing anvil supports the lower sheet. The rotation speed, ω, the normal force, F, and the tool insertion rate are maintained for an appropriate time known as the process time, t_p. The rotating tool causes stirring in both the top and bottom sheets, generating frictional heat, which softens the material and material adjacent to the tool deforms plastically, thereby creating a solid-state bond between the upper and lower surfaces of the sheets to be joined. Unlike the linear FSW, which moves in the transverse direction to form a continuous linear joint, the SFW tool is retracted when the stirring process is finished at the particular spot (Fig. 1c). This leaves a characteristic center hole equal to the pin diameter at the center as shown in Fig. 2.

The SFW process can be controlled by either load control or displacement control. Among the parameters used to control the SFW process, the most critical parameters are tool rotational speed (ω, rpm), process time (t_p), the normal load, F, applied on the tool to the sample, tool insertion depth (DoP) into the sample, and tool insertion rate into the sample. Details of the tool shoulder surface and pin tip may also be important [10,11]. However, a tool with a cylindrical shank and a projection pin with smooth surfaces or threads are sufficient to produce a good quality weld.

1.2. *Effect of Welding Parameters on Strength*

A comprehensive review article published recently [6] provides details on the joining technology, process parameter development and variations of the process used to join not only aluminum alloys, but also dissimilar metals such as steel to steel, steel to aluminum, and aluminum to magnesium. Recommendations to improve the SFW process and increase joint efficiency are also provided. Good lap-shear strength of SFW joints has been reported in the literature [7–9]. The strength has been shown to be dependent on the above-mentioned critical parameters. For example, Fujimoto et al. [8] and Pan et al. [9] observed that increasing processing time, t_p, increases both the tool DoP and the shear strength for 1.0 mm/1.0 mm thick 6111 aluminum alloys welded in lap-shear configuration.

Effect of tool rotation speed on joint strength, strain rate and temperature distribution have been the subject of recent studies [10–13]. Temperature of the stir zone was measured by embedding K-type thermocouples in the tool [11]. For friction stir spot welded 2024 aluminum alloy [10], the strain rate, $\dot{\varepsilon}$, was estimated by using an empirical relationship between the measured subgrain diameter and the Zener–Holloman parameter, Z, where Z is given by [14]:

$$Z = \dot{\varepsilon}\ \exp\left(\frac{Q}{RT}\right) \tag{1}$$

where T is the deformation temperature, Q is the activation energy and R is the universal gas constant. It was observed that the strain rate decreased drastically from 1600 s^{-1} to 0.6 s^{-1},

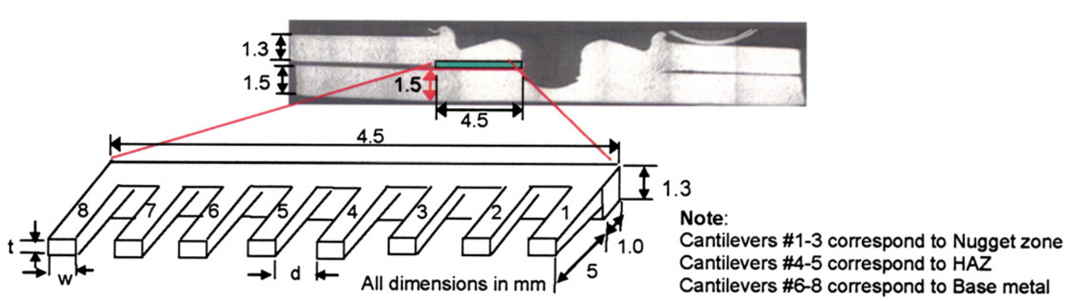

Fig. 2 – SFW microcantilever array design and the location of the sample machined by wire EDM.