A Review: Dissimilar Material Joining of Metal to Polymer using Friction Stir Welding (FSW)

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Abstract

Techniques for joining of lightweight dissimilar materials, particularly metals and polymers, are becoming increasingly important in the manufacturing of hybrid structures and components for engineering applications. The recent trend is towards lightweight construction in the aerospace and automotive industries, which has led to increased requirement in lightweight metallic and non-metallic materials with the aim of achieving specifically optimized versatility. Hence, suitable joining methods are necessary, in order to reliably join these dissimilar materials and to integrate them in engineering structures. Understanding of the various joining technologies that exist for multi-material, metal-to-metal, polymer-to-polymer, and metal-to-polymer hybrid structures is consequently becomes important. The objective of current study is to examine and summarize information and results from previous research and investigations on friction stir welding (FSW) for joining dissimilar materials. The findings presented serve to further understanding of the FSW advantages over other convectional processes and optimization of processes for metal-to-metal, polymer-to-polymer and metal-to-polymer hybrid joints.

Keywords: Friction stir welding (FSW; Dissimilar materials; Polycarbonate (PC); high density polyethylene (HDPE); Aluminium Alloy (AA)

I. Introduction

Utilization of plastic materials in engineering structures has increased because of benefits accruing from their low weight, high specific strength and elastic modulus, design flexibility, and reduced manufacturing costs [1, 2]. The increasing applications of polymer materials in structural applications result in increased focus of research into joining methods of metal-polymer. Parts made by combining dissimilar materials such as metal-to-metal, polymer- to-polymer, and metal-to-polymer are nowadays in demand e.g., body parts in modern automobile structures as reinforced plastics wing & in modern aviation structures as fuselage sections. In addition, composite materials such as carbon-fiber-reinforced polymer (CFRP) or glass-fiber-reinforced polymer (GFRP) are also integrated to lightweight metals such as aluminum or magnesium for a very strong and lightweight hybrid structure [2].

One of the aims for the use of dissimilar joints is to enhance product design flexibility, allowing the differing materials to be utilized in an efficient and functional manner based on the specific properties of each material. Metal-to-polymer joints, on the other hand, combine the strength and ductility of the metal with the good chemical resistance and light weight of the polymer [3]. The metal component is utilized in sections where high stiffness and strength can be exploited, whereas the plastic material provides unique chemical properties, and enables formation of complex shapes in the molding process. However, joining of dissimilar materials is often difficult to achieve and the behavior of such joints is rarely fully understood. The most frequently used joining methods for dissimilar materials are mechanical fastening and adhesive bonding [2]. However, these joining processes present several limitations, such as stress concentration, the demand for extensive surface preparation, extra weight, material metallurgical differences and harmful environmental emissions.

Different promising welding techniques and approaches for joining dissimilar materials have been developed as a way to address problems related to convectional joining techniques. Examples of such new emerging techniques are ultrasonic welding, laser welding, friction spot welding, and friction stir welding. This paper presents a comprehensive overview of FSW for joining dissimilar materials found in metal-to-metal, polymer-to-polymer and metal-to polymer joints. The paper comprises following sections. First gives general introduction to concepts and the requirement to join dissimilar materials. It also explains about the Friction Stir Welding process. The second part of the paper focuses on the research done by different researcher on welding of dissimilar materials. The welding of metal-to-polymer is given greater emphasis in this section than metal-to-metal and polymer-to-polymer welding, since metal-to-polymer is a novel technique and there are limited publications in this area. The third section

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of the paper presents the research gap and the possible future work that can be done on dissimilar joining of metal-polymer. The final section summarizes the remarks about the topic.

A. *Friction Stir Welding:*

FSW was invented by Mr. Wayne Thomas at the welding institute (TWI) and the first patent applications was filed in the UK in December 1991 [4]. In very beginning, the process was regarded as a ”laboratory” curiosity, but it rather soon became evident that it had a lot to offer in the fabrication of aluminium products.

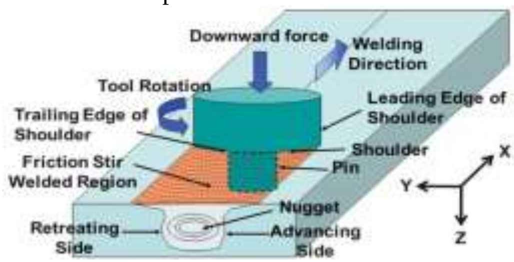


Fig. 1: Process principles for friction stir welding [5].

In FSW, a cylindrical shouldered tool with a profiled pin is rotated and plunged into the abutting edges of plate material. The parts have to be securely clamped in a manner that prevents the joint faces from being forced apart. Frictional heat between the wear resistant welding tool and the work pieces causes the later to soften without reaching the melting point and allows traversing of the tool along the weld line. The plastically softened material is transferred to the trailing edge of the tool pin and is forged by the intimate contact of the tool shoulder and the pin profile. On cooling down, it leaves a solid phase bond between the two pieces.

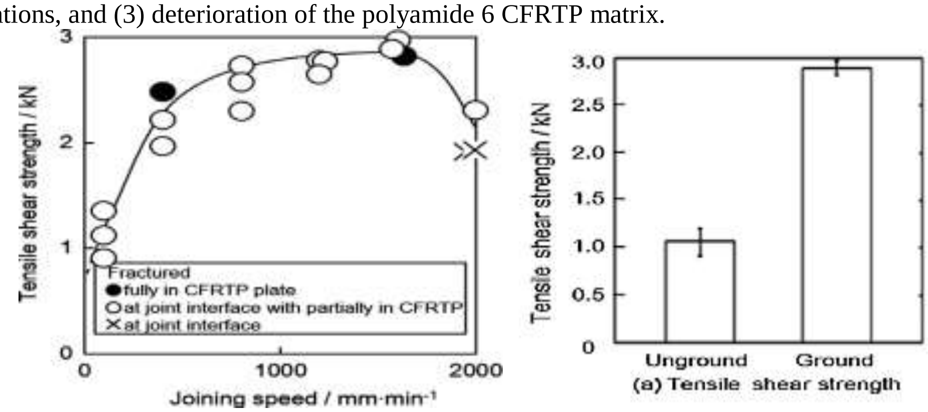
FSW can be used to join aluminium sheets and plates, without filler wire or shielding gas. Materials variety ranging from aluminium alloys, copper, magnesium, lead, zinc and polymers and material thickness ranging from 0.8 to 65 mm have been reported for successful welded joints at full penetration and without porosity or internal voids [6].

PROPERTIES OF FRICTION-STIR WELDED DISSIMILAR JOINTS

B. *Tensile Strength Analysis:*

As reported by researchers, tensile strength of friction stir welded joint of similar or dissimilar metal joint increase with tool rotational speed (RS) up to certain optimum value then decreases [7-9]. This effect is attributed to grain coarsening, blur and overheating at higher RS due to higher frictional heat. This leads to lower joint strength. Tensile strength analysis of friction stir welded joint of metal to polymer reported by various researches is described in following section.

Kimiaki et al. [7] have reported the relationship between the joining speed and the resulting tensile shear strength of the lap joint of Al-5052 to carbon-fiber–reinforced thermoplastic (CFRTP). The tensile shear strength has been increased with the joining speed up to 1600 mm/min, and then decreased at 2000 mm/min as shown in Fig. 2(a). Maximum tensile shear strength of the joint fabricated at 1600 mm/min is reported 2.9 KN. The same is attributed to (1) generation of voids in CFRTP, (2) irregular carbon fiber orientations, and (3) deterioration of the polyamide 6 CFRTP matrix.



(a) (b)

Fig. 2: (a) The relationship between joining speed during FLJ and the tensile shear strength of the joints (b) Tensile shear strength of the unground- and ground-A5052/CFRTP joints [7].

Effect of grinding on the tensile strength of lap joint has also been reported, as shown in Fig. 2(b). Tensile shear strength of the unground-A5052/CFRTP joint is 1.0 kN whereas, grinding treatment leads it to 2.9 kN. The unground-A5052/CFRTP joints possessed weak interfacial strengths, and therefore the fracture mainly occurred at the interface between the materials, which leads to lower strength. Whereas the ground specimens having good surface conditions led to strong interfacial strength.

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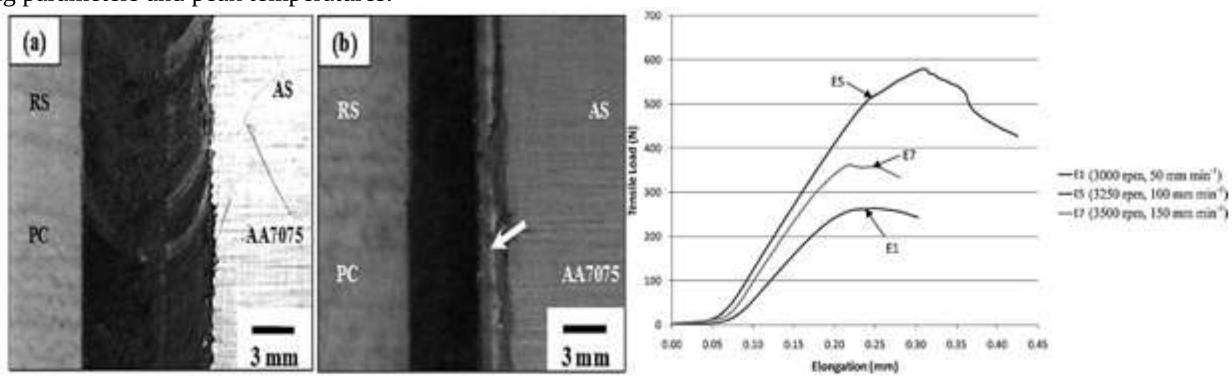
R. Moshwan et al. [9] have evaluated the effect of the tool rotational speed and traverse speeds on the tensile strength of friction stir welded AA 7075 to PC joint. A representative surface appearance of the welded joint at 3,500 rpm and 50 mm/min is shown in Fig. 4(a) & (b). The influence of the tool rotational and traverse speeds on the tensile strength and elongat-ion of the friction stir welded joints is shown in Fig. 4(c). As shown in Fig. 4(c), at 3 250 rpm with the increase of traverse speed the tensile load increases while it is inconsistent at 3000 and 3500 rpm. A highest tensile load of 586 N was obtained at 3250 rpm and 100 mm /min, while the lowest value of 310 N can be obtained at 3500 rpm and 150 mm/min. Tensile strength and hardness of the welded joints were lower compared with those of the base materials owing to the presence of scattered particles and voids at the joint interface, the transportation of AA 7075 to PC, and kissing bonds. The transportation of AA 7075 was highly influenced by welding parameters and peak temperatures.



(a) (b) (c)

Fig. 4: Surface appearances of the welded joint at 3500 rpm and 50 mm min–1 (a) front side (b) rear side (c) Tensile load curve for highest, middle, and lowest load. [9]

C. Hardness Analysis:

As per the results, reported by researchers, hardness of the welded joint largely depends on heat input and thereby amount of grain refinement [9, 10]. Higher hardness has been reported in the area of higher grain refinement and dislocation strengthening.

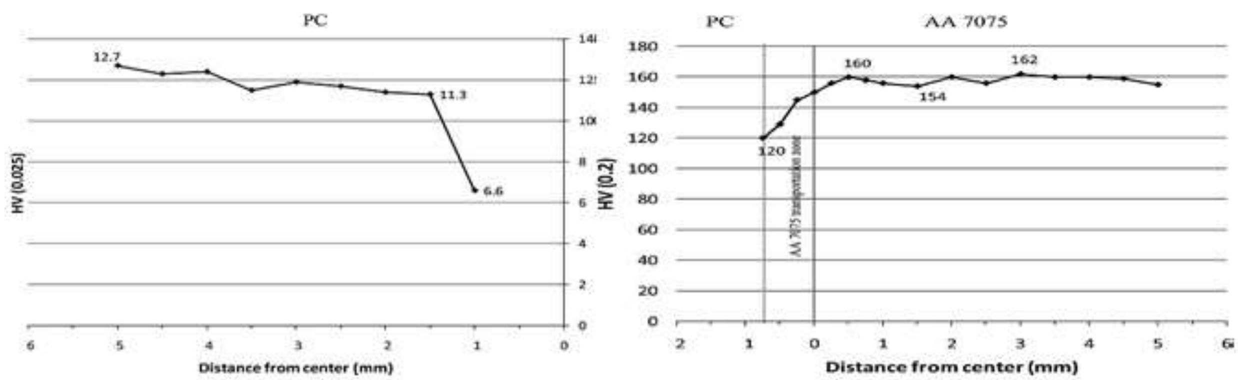


Fig. 5: Vickers micro hardness at PC joint interface and at AA7075 base material and AA 7075 transportation interface. [9]

R. Moshwan et al. [9] have studied friction stir welded joint properties of PC to AA 7075. The value of Vickers microhardness at the joint interface on the PC side at a distance of 1 mm up to 5 mm from the welding center line is shown in Fig. 5. As shown in figure when the distance from the welding centerline increases, the hardness increased. The lowest hardness value of 6.6 HV0.025 was obtained at 1 mm on the PC side. The value of Vickers microhardness at the joint interface on the AA 7075 side was measured at a distance from 0.75 to 5mm from the welding center line shown in Fig.5. The hardness reduction has been clearly observed in the welded area of the PC side, caused by thermal degradation due to the tool stirring and frictional heat that softened the material and decreased its hardness. In general, the reduction in grain size would increase the hardness at the welded zone.

D. Characterization of the Microstructure:

Microstructure of metal to polymer joint as reported by researchers is found to be difficult to analyze due to different material physiology and morphology [8, 9]. Interlocking mechanism between the aluminum to polymer joints has been observed in the welded joints.

R. Moshwan et al. [9] have studied the microstructure characteristics at the joint interface for Al 7075 to PC joints fabricated by FSW. The grain boundary images taken at AA7075 base material and AA 7075 transportation are shown in Fig. 8a and b, respectively.

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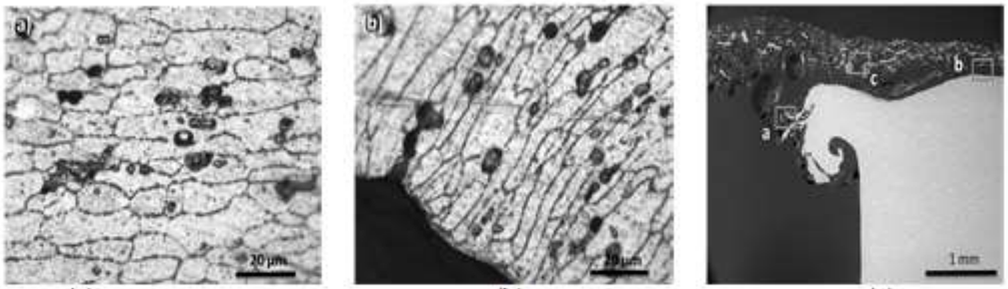

(a) (b) (c)

Fig. 7: Grain boundary images taken at (a) base material AA7075 and (b) AA7075 transportation and SEM image of cross-section joint interface for PC–AA 7075 with welding parameters of 3250 rpm, 100 mm/min [9]

In general, the grains elongate to more than 40 µm, and the corresponding grain width significantly reduces. Spectron electron microscopy (SEM) image for the PC–AA 7075 joint welded at a tool rotational speed of 3250 rpm and a traverse speed of 100 mm/min is shown in Fig.7. It can be observed that AA 7075 is transported and interlocked into the PC structure.

Ratanathavorn et al. [8] have observed the microstructure of the dissimilar joint. Fig.8a shows the microstructure of the weld consisting of aluminum chips surrounded by thermoplastic matrix.

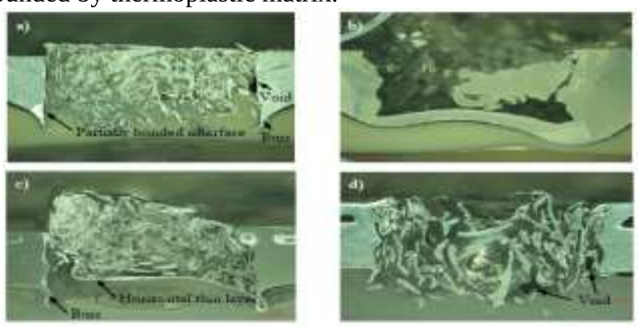

Fig. 8: The micrographs of aluminum-thermoplastic joint cross. a) AA5754 (1.5)-PP joint welded with 1800 rpm, 10 cm/min b) AA5754 (2.0)-PP joint welded with 1800 rpm, 10 cm/min c) AA5754 (1.5)-PA12 joint welded with 1800 rpm, 10 cm/min d) AA5754 (1.5)-PA12 joint welded with 1800 rpm, 20 cm/min.[8]

The direction of molten thermoplastic flow is controlled by threaded pin to flow in vertical direction near the pin towards the shoulder. Voids can be seen at retreating side (right-hand side of cross-sectional micrographs) in case of clock-wise rotation. It is evident from Fig.8a that partially bonded interfaces between aluminum parent material (upper plate) and aluminum-thermoplastic composite weldment can be visually seen at some welding parameters. Fig.8c and 8d show the effects of tool travel speed on aluminum chip morphology and existence of horizontal thin layer. It can be seen that low travel speed results in fine aluminum chip weldment compared with higher travel speed.

II. RESSEARCH GAP AND FUTURE SCOPE

FSW has very attractive prospect because of energy efficient, cost-effective and versatile operation. Although there have been several studies carried out on FSW of dissimilar metals for past few years, the research on FSW of dissimilar materials such as polymer–metal is still in its infancy. The understanding has been useful in reducing defects and improving uniformity of weld properties and, at the same time, expanding the applicability of FSW to new engineering materials. Some findings for future prospects are listed below:

1) Most of the researches reported are focused on similar joints like Al alloy to Al alloy, Mg alloy to Mg alloy using FSW and limited is available for dissimilar metal as well as materials e.g. Metal to polymer
2) Limited studies have been reported for effect of feed rate, tool tilt angle, weld line offset, tool tip profile on the joint properties for dissimilar material joining.
3) There is huge potential in the present area to analyses the influence of the processing parameters on the transition, plunging and welding stages.

III. CONCLUSION

Friction stir welding technology has been a major boon to industry advanced since its inception. In spite of its short history, it has found widespread applications in diverse industries. This paper has clearly demonstrated the properties such as tensile strength, microhardness and microstructure of the metal to polymer FSW joint. In addition, it has also shown that the feasibility of friction stir joining of dissimilar materials; metal and plastic. The main conclusions can be summarized as follows:

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1) It is become feasible to joint aluminium alloy and polymer plates with a friction stir welding.
2) Tensile strength and hardness of the welded joints were lower compared with those of the base materials owing to the presence of scattered particles and voids at the joint interface. The transportation of metal particles was highly influenced by welding parameters and peak temperatures.
3) The hardness reduction was clearly observed in the welded area of the polymer side, caused by thermal degradation due to the tool stirring and frictional heat that softened the material and decreased its hardness. In general, the reduction in grain size would increase the hardness at the welded zone. The strain exerted by the process tends to elongate and reduce the width of the grain.
4) The microstructure images reveal that the joining mechanism between metal and polymer is thought to be a mechanical bonding rather than a molecular bonding of the materials.

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