Joining of aluminium to polymer by friction stir welding: An overview

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Abstract. Friction stir welding (FSW) is a potential fabrication method to join the aluminium and polymer dissimilar materials as FSW joins the metals below their melting point. Since the automobile and aviation industries replacing the heavier metals with the lighter one like aluminium and polymer therefore joining of these two materials is the requirement for the industries in the current time. A lot of studies have been already done to join these two materials in the lap, butt and t-joint configuration. Particular attention has been focused to macrostructural and microstructural evolution after welding, microhardness and tensile property. As the temperature is an important factor for both the polymer and aluminium due to difference in chemical and mechanical property, so FSW is a suitable technique compared to other fusion welding processes therefore improved joint property is expected. In the present study, process capability of FSW has been enlightened for joining aluminium-polymer materials for future prospective…

1. Introduction

Automobile industry always looks for materials that reduces the weight of component and environment friendly and so polymers utilization has increased in these industries[1]. Polymers have high specific strength, low thermal expansion, excellent fatigue and fracture strength[2]. Polymers are light weighted and easily formable substances and these are much needed property for automobile and aerospace industry. The technologies such as roll drawing and hydrostatic extrusion has produced polymers with the strength and module comparable to that of metals[3]. Polymers lack in ductility so there usage along with metals such as aluminium, steel, magnesium and etc are done. Automobile industries have replaced the steel components with aluminium as the later gives strength even at reduced mass improving power to weight ratio[4]. Aluminium is a less dense material with good ductility therefore it is joined with polymer to extract its advantageous properties. Aluminium and polymers are used for making vehicle panels and battery housing[5].
There are 3 main methods for joining aluminium and polymers; these are (1) Adhesive bonding (2) Mechanical fastening and (3) Welding as shown in fig. 1. Resins used for joining Al are epoxies, acrylics, phenolics and temperature resistant polyimides. These resins gets hardened on polymerization or condensation[3]. Surface treatment such as etching and anodizing is done when joints are formed. Adhesive bonding is susceptible to environmental degradation even little amount of moisture degrades the strength as well as a small penetration can destroy the joint [6]. In mechanical fastening method components such as rivets, bolts, etc are used for joining metals and polymers. The problem encountered in this process is that it requires holes in the material which gives rise to stress concentration[1,7]. In aerospace industry adhesive bonding along with mechanical fasteners are used. Sadowski et al [8] reported that when adhesive are used with rivets then energy absorption before facture has increased to 64% compared to when adhesive bonding was used alone. Tensile strength was increased to about 11% to that of analogues bonded joint and 130% to that of simple riveted joint [7,8]. Direct welding of Al and polymer is not possible as they are structurally dissimilar. Polymer have a open structure comprising of chain of micro molecular monomers on the other hand aluminium is a densely packed crystalline structure[1,9,10]. Welding can only be done for thermoplastic as welding requires melting and thermosetting plastics cannot be melted[10]. Welding of al and polymers can be done in various ways but ultrasonic, laser, friction spot welding and friction stir welding gives improved results[1]. Belle et al [11] performed ultrasonic spot welding of aluminium and carbon fiber reinforced polymer (CFRP) and revealed that a tensile shear strength of 30 MPa can be achieved within a welding time of 5 seconds. Laser welding of aluminium and CFRP can be produced using disc type laser[12]. Friction stir spot welding (FSSW) is similar to FSW with a difference that there is no linear movement of the tool. Rotating tool produces heat which is utilized for welding process. Paider et al. [13] performed friction FSSW of aluminium and PP-C30S polypropylene polymer having thickness of about 1.7 to 2mm thickness using a pre-threaded hole in the aluminium plate for mechanical interlocking. It was revealed that with the increase of tool rotational speed thickness of reaction layer increases from 70 to 100 µ also the shear-tensile and cross-tensile load of the hybrid joint increases[13].
FSW is a solid state welding method which utilizes the friction between rotating tool with a probe and the parent material for producing heat and when sufficient heat is achieved then tool is moved in linear direction. Khodabakhshi et al [14] performed FSW of aluminum and denosed polyethylene. It was revealed that joining occurs due to mechanical interlocking and adhesion between metallic Al chips and consolidated polymeric layers by interface chemical reaction. Formation of thin Al2O3 nano-scale (30 nm) layer was observed at the Aluminum and polymer interface[14].

![Figure 3 FSW of aluminum alloy and high polycarbonate](image)

2. Macrostructure

![Figure 4 Macroscopic view of the Aluminum polymer lap joint](image)

![Figure 5 Macrostructure of the Al-polymer lap joint at a) 30 mm/min b) 50mm/min c) 70 mm/min d) 90 mm/min welding speeds](image)

Figure 4 is representing the welding zone of the aluminum polymer lap joint. Identifying the different weld zone is the most difficult part visually, specially the HAZ. Derazkola et al. [16]used FSW technique to join the AA5058 and PMMA polymer, and distinguish the different region in the welded
part as shown in fig. 4. A wider heat affected zone along the advancing side represents the higher heat input. Fragments of aluminum were observed in the melted and re-solidified PMMA matrix. A U-shape structure with two aluminum ramus was observed at the middle of the stir zone. Ramus were observed towards both sides advancing side and retreating side respectively along the joint line. Since the shoulder is in immediate contact with the PMMA therefore most part of the heat resides in the PMMA which restricts the plasticization of aluminum along the joint line due to the low thermal conductivity of PMMA. However ramus are helpful in enhancing the macro and micro mechanical interlocking between the materials which improves the tensile property of the joint. The shear and stirring action helps in the improved material mixing in the weld stir zone. Huang et al. [17] used FSW technique to join the PEEK polymer and AA6061. Aluminum was placed over the PEEK polymer. The most part of heat generated inside the aluminum alloy thus restricts the movement of polymer outside the weld zone. Apart from the stir zone aluminum arrow were observed along thermo- mechanically affected zone, retreating side and advancing side as shown in fig. 5. The aluminum arrow at joint interface develops a mechanical interlocking and thus improves the tensile property of the joint. The aluminum anchor along the advancing side is bigger than the retreating side due to the high heat input along the advancing side thus results in proper softening of the aluminum alloy. The length of this anchor increases and decreases with the variation of heat input. The length of the anchor sharply decreases with further increase the welding speed to 90 mm/min

3. Microstructure

Figure 6 SEM image of different stir zone region a) fragmented aluminum particle b), c) Distribution of aluminum in the stir zone

Figure 7 Cross sectional SEM image of Al-PMMA T-joint a) whole cross section b) advancing side C) retreating side d) interfacial layer

The weld stir zone of Aluminum-Polymer joint is characterized by the interlock phenomena and transport of aluminum into the polymer[18]. On the basis of aluminum distribution, stir zone is divided into three distinct region: parent material (Fig.6a), aluminum mix composite structure (Fig.6b
& 6c) and interfacial zone (Fig. 7d). The aluminum particle transported and locked inside the polymer. Movement of these aluminum plays a big role in defining the tensile strength. Severe defects such as void are noticed in the nugget zone as shown in fig. 6a. Derazkola et al. [19] joined AA5754 and PMMA in T-joint configuration and studied the microstructure of the joint as represented in fig. 7. Fewer aluminum fragments are observed along retreating side as compared to the advancing side. Stretched aluminum ramus observed near the interfacial area of Al-PMMA. The heavy lines acts as mechanical interlock between the aluminum-PMMA. Interaction layer is observed between the lower area of aluminum ramus and PMMA without any defects and voids (Fig. 7d). So the joining mechanism depends on the mechanical interlocking, adhesion bonding between the Al/PMMA at interface and distribution of Al fragments in the stir zone.

4. Micro-hardness

Butt and lap joint are the two most common methods to join the aluminum and polymer. So the hardness is measured along the different lines to cover the entire zone of the weld zone. Sahu et al. [20] measured the microhardness along the center line of friction stir welded Al6063 and polypropylene in butt joint configuration as shown in fig. 8. The microhardness decreases continuously from the aluminum side to the weld center line and increases from the centerline to the interface along the polypropylene side. The highest microhardness of 132HV was observed at 2.5 mm from the weld center line along the aluminum side due to the formation of carbon based brittle compounds at the interface. Measuring of microhardness along the center line does not include aluminum HAZ in lap joint if polymer is placed over the aluminum alloy. Derazkola and Elyasi [21] measured the microhardness along shoreD line and HV line in lap welded AA5058 and polycarbonate as shown in fig. 9. Fig 9 b showing the hardness of polycarbonate reduced after the welding compared to the base polycarbonate material. With the increase in rotational speed the hardness of the resolidified polycarbonate decreases due to the frictional heat at the time of process lead to the molecular weight reduction. Derazkola and Khodabakhshi [22] claimed that the frictional heating increases the rate of the dynamic recovery and consequent dynamic recrystallization of the aluminum alloy at the time of mixing with polymer in weld zone, reduces the hardness. Derazkola and Simchi observed that the any experimental parameter which affects the size and volume of the aluminum in weld zone affects the hardness distribution.

![Figure 8 Microhardness of Al6063 and polypropylene along the center line](image-url)
5. Bonding mechanism

Mechanical interlocking and chemical adhesion are the main bonding mechanisms for development of dissimilar welding between aluminum and polymers[23]. Chemical bonding occurs due to transfer of charge from metal atoms to polymer molecules[24]. Transfer of charge between metal and polymer results in the formation of metal-polymer complexes[24] and these results in chemical adhesion between metal and polymer. Metal surfaces are generally rough when observed on microscopic level. So when liquid polymer is applied to the rough surface then the liquid flows into the holes, dips and microgrooves and conforms to them thus resulting in the formation of interlocking between aluminum alloy and polymers[25]. Yusof et al [25] performed FSSW of aluminum alloy and polyethylene terephthalate (PET) and revealed that the bubbles formed during the welding help in interlocking. Friction stir welding melts the PET and leads to bubble formation near the joining interface due to the heating. Bubbles push the melted polymer in liquid phase into the roughened metal surface where mechanical interlocking occurs and joint strength gets improved[25]. More bonding area is formed when high heat is produced during welding process and it gives better bonding strength[26].

6. Tensile properties

Tensile property of aluminum alloy and polymers fabricated by FSW depends upon various process parameters. These process parameters include positioning of material, speed of rotation, tilt angle, penetration depth and welding speed. Dalwadi et al. [27] friction stir welding of aluminum alloy and acrylic and revealed that on increasing the tool rotational speed joint strength of the welded joint increases but when the welding speed or tool feed is increased then tensile strength first increases up to 40mm/min and there after it goes on decreasing[27]. A maximum joint strength of 7.06 MPa was achieved at1000 rpm and 40 mm/min which is 20% less then PMMA (acrylic) as shown in fig. 10a.
Whereas increasing the tool feed first increases and then decreases the strength of the joint (figure 10 (b)) [27]. Derazkola et al [16] reported that the tilt angle and penetration depth also affect the strength of the welded joint.

With the increment in tool tilt angle, the ultimate tensile strength increases as shown in fig. 11. Similarly increment in ultimate tensile strength was registered from the plunge depth of 0.1 mm and 0.2 mm and it decreases at the plunge depth of 0.4 mm. This happens because at high plunge depth excessive heating and inappropriate micro and macro interlocking occurs. The highest tensile strength of 45 MPa was obtained at 2° tilt angle and 0.2 mm penetration depth [16]. Derazkola et al [28] employed FSW to join the Al-Mg alloy and poly methyl methacrylate in lap joint configuration. The maximum joint strength obtained was 45.5 MPa obtained at 1250 rpm and 50 mm/min.

7. Conclusion
A brief review on the joining of polymer to aluminum is presented. The main purpose of the article was to study the effect and distribution of material flow on the mechanical properties like tensile strength and microhardness. Article also covers the bonding mechanism between both the materials which is an important factor for the joining

1. Three different joint configurations are possible such as butt joint, lap joint and T joint. The lap joint can be performed by keeping either aluminum on the top or polymer on the top.

2. Ramus or mechanical arrows are formed at the interface in both the lap joint configurations which enhances the mechanical interlocking and thus the tensile property.
3. Frictional heating affects the microhardness profile in the stir zone due to the dynamic recovery and consequent dynamic recrystallisation.

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