Experimental Investigation to Join Al 6063 Alloy to Polypropylene using Friction Stir Welding

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Abstract

Now-a-days lightweight materials like aluminium alloys, thermoplastics and its hybrid structures are highly used in the aerospace, automotive sectors due to its high strength to weight ratio with excellent corrosive resistance. However, metal to plastic joining is quite often difficult because of the drasticdifference in their thermal, mechanical and chemical properties. Though there are works on dissimilar joining, there are hardly few works on aluminium to thermoplastics using friction stir welding. Thus, the aim of this study is to check the feasibility of friction stir welding between aluminium alloys Al 6063 to polypropylene, focused on a parametric study on joint efficiency using K-type thermocouples and axial force dynamometer signals. Three variables i.e. tool rotation, traverse welding speed and tool tilt angle were considered for butt welding. Initially, a threaded cylindrical tool without any offset located centrally for welding resulted poor joint efficiency. Then, an offset of 1.5mm in the aluminum side was set to ensure better mixing of plastic to aluminium. Further, another approach with a slot on aluminium side have also been developed for the same. However, the maximum joint efficiency was found to be below 10% at moderate tool rotation (750 rpm) with adequate traverse speed (25 mm/min) at 2^0 tool tilt angle due to adequate mixing of aluminium to thermoplastic. The joint quality degrades due to materials expulsion or improper material flow from advancing to retreating side at higher or lower rotational speed, respectively. The joint quality affected due to the variation of welding speed in a reverse way. There were several kind of defects like excessive expulsion of materials, clusters of materials around the tool pin and large number of micro-voids in the weld bead as per micrographs due to low solubility caused by different bonding structure of parent materials which significantly reduce the joint strength.

Keywords: Friction stir welding, light-weight materials, thermoplastics, process parameters, tensile strength

1. INTRODUCTION

High performance light weight metals and plastics are playing a vital role in the manufacturing sectors. In these recent years raw materials used in aerospace, automotive industries have been shifted from conventional materials like steel, iron to lightweight materials such as aluminum, magnesium [1] and some high performance plastics such as polypropylene, PVC, polyurethane [2]. It is estimated that the average use of plastics in a particular standard vehicle is 150 kg against iron and steel. This means reduction in weight which is around 10-15 % of total weight of the car [2] due to difference in their densities and every 10% reduction in weight results in 5%-7% reduction in fuel usage. Use of plastics is increased for structural applications because of benefits that arises from low weight, high specific strength, thermal and electrical insulation, excellent corrosion resistance, more degree of freedom in designing and at low manufacturing price [2-5]. However greater amount of concentration is paid on the metal-plastic hybrid structures but joining metal and plastics is quite often difficult. The main reason for this Difference is the thermal, mechanical and chemical properties. The most traditional ways to join metal and plastics are mechanical fastening and adhesive bonding but possess large number of limitations. Adhesive bonded materials cannot be disassembled without damage and also the bonded joints are prone to climatic changes such as moisture, humidity and temperature. On the other hand, increased component weight due to overlapping of plates and use of fasteners like nuts and bolts, stress concentration around fastener holes and corrosion limits the use of mechanical fastening. Thus, several advanced techniques were developed such as ultrasonic welding, laser welding to overcome these limitations.

Friction stir welding overcomes these limitations in a better way. Friction stir welding (FSW) was invented by The Welding Institute (TWI) in December 1991 [6]. It is a solid state joining process that uses a third body tool to generate frictional heat between tool and work piece and this heat is being used to soften the material near the tool so that weld joint is formed. A non-consumable rotating tool with specially designed shoulder and the pin is inserted into the abutting edges of the plates to be joined and is allowed to rotate for some time at that particular point then the tool is allowed to move in transverse direction along the joint line and at last the tool is retracted back. The tool when pulled out, leaves a footprint in the form of a keyhole which has same size and appearance as that of tool pin.

It had been proved the potentiality of FSW by obtaining a joint efficiency of 90% with respect to the plastic base material. FSW of Polyethylene sheets was studied by Erica Anna Squeo et al. [1] in which the effect of preheated pin and base plates on the tensile strength was studied. It was observed that preheating the base plates and higher contact time of heating leads to increase in the tensile strength of joint using 1mm diameter tool steel pin. F.C. Liu et al., studied friction stir lap welding of metal to plastic [7]. It was observed that bubble generation takes place when the temperature of the welded region goes beyond the decomposition temperature (325 ^{0}C for MC Nylon 6) which results in pyrolysis effect and the byproducts were gases of hydrocarbon, carbon dioxide, carbon monoxide. The

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nominal shear strength was in between 4.5MPa to 8MPa. H. Shamiri et al. studied friction stir lap welding of aluminum to polypropylene sheets [8]. It is observed that a sound joint with low distortion was achieved by friction stir lap welding with 20% joint efficiency. A distinctive interaction layer was found consisting mainly of C, O, Al with a gap formation between the interaction layer and the base materials due to difference in their coefficient of thermal expansion. Therefore, thermal stresses were found to be induced at the joint portions. The gap size increased with the increase in rotational speed due to more heat generation. Thus, maximum joint strength was obtained for low rotational speed. F. Khodabakshi et al. studied microstructure property characterization of a FSW joint between AA5059 aluminum alloy and high density polyethylene plates of 4mm thickness [9]. The mechanical interlocking had been noticed between aluminum layers and enclosed polymer matrix. The bright grey contrast represents the AA5059 layers and melted re-solidified HDPE matrix was indicated by dark grey contrast. Thus, mechanical interlocking and chemical adhesion was the main bonding mechanism to develop that dissimilar joints. W. Ratanathavorn and A. Melander studied friction stir lap welding of AA6111 and polyphenylene sulphide [10]. It is noticed that higher value of Distance to backing (DTB) causes less plunging of tool inside the materials to be welded. The process parametric effect on stir zone and formation of fracture had been studied. It was observed that the sizes of the metallic fragments in the stir zone are closely linked to the translational speed, with rapid translational speeds tending to create coarser fragments. A reduction in the value of DTB during welding leads to more plastic filled region between chip nugget region and aluminum base material which increases the failure chances of the joint. Mechanical interlocking at the stir zone is the main factor contributing to the tensile strength of the joints. Raza Moshwan et al. studied friction stir welding of AA7075 aluminum alloy and polycarbonate plate of thickness 3 mm [11]. EDX and XRD analyses revealed that no significant mixing occurred between PC and AA7075 and no ceramic type compound was formed at the joint interface.

In the last twenty years, several works have been carried out to improve joint efficiency in various joining processes for aluminum to thermoplastics. These works mainly focus on improving weld quality by adjusting various parameters using friction stir welding, laser welding and ultrasonic welding etc. But a few works have been performed using FSW on aluminum to thermoplastics and also there is hardly any work done related to axial force and temperature during welding. Thus the aim the experiment is not only to check the feasibility and parametric effect on friction stir welding between aluminium alloys Al 6063 to polypropylene but also to analyze the effect of change in specimen design, parameters on axial force and temperature generation during welding.

2. EXPERIMENTAL PROCEDURES

The base material selected for the experiment was aluminum and polypropylene sheets of size 100 mm x 100 mm x 6 mm. The mechanical and physical properties of the base materials have been indicated in Table 1 and the chemical composition of Al 6063 is listed in Table 2. A schematic representation of the FSW experimental procedure is shown in Fig. 1. Polypropylene is light weight thermoplastic with a wide range of properties and applications. It can be joined by using any common joining techniques. The H13 tool steel FSW tool used for this investigation had been machined to form specially designed threaded cylindrical shape. It has a shoulder diameter of 25 mm, pin diameter of 6 mm and pin length of 5.6 mm as shown in Fig 2.The tool shoulder portion was concaved surface with 6^0 angle so that it can prevent expulsion of material from the welding zone.

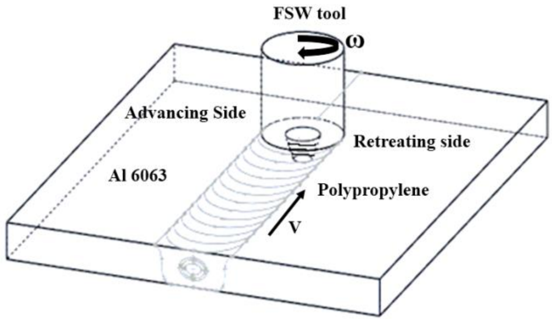

Fig. 1 Schematic diagram of FSW experimental procedure

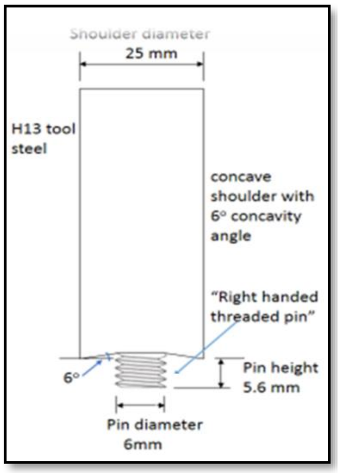

Fig. 2 Cylindrical threaded FSW Tool

The aluminum and polypropylene sheets were butt welded using a 2 ton, 3 axes NC controlled FSW machine as shown in Fig. 3. Initially, the samples were cut in a Do All cutting machine and then have been fixed on the fixture maintaining zero gap. The bolts were tightened properly and the bed is kept fixed. Friction stir butt welding of aluminum alloy Al 6063 and polypropylene have been achieved but the weld joint was not appreciable due to improper mixing of 2 materials as per optical image of weld bead samples. In order to ensure proper mixing the design of the base samples to be welded were slightly changed. Firstly, the internal slot of dimensions (100 mm x 12 mm x 3.5) was made along the longitudinal direction of the Al 6063 and then PP of thickness 3.5mm is allowed to insert into the aluminum groove as shown in the Fig.4.

Table 1: Mechanical and physical properties of AL 6063 and polypropylene

Materials	Density ($\times 10^3$ kg/m^3)	Elastic Modulus (GPa)	Yield strength (MPa)	Tensile Strength (MPa)	Melting Temperature (°C)
AA6063	2.7	70-80	48	130	650
PP	0.91	0.9	35	33	160

Table 2: Chemical composition of AA6063

Material	Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn
AA6063	0.436	0.361	0.041	0.102	0.485	0.0154	0.0215	0.0378

Fig. 3 FSW machine set-up

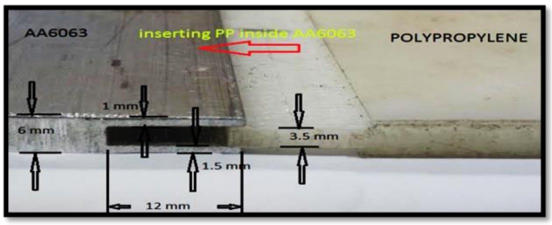

Fig.4 Slot type design of base weld plate

Table 3: Process parameter values with joint strength

Experiment no.	Rotational speed (rpm)	Translational speed (mm/min)	Tensile Strength (MPa)
1	400	15	0.36
2	400	25	0.65
3	400	50	0.46
4	750	15	0.54
5	750	25	0.97
6	750	50	0.88
7	1000	15	0.19
8	1000	25	0.43
9	1000	50	0.28

Table 3 shows the different process parameters chosen for the experiment study. The experiments are based on full factorial method. The experiment set was repeated three times to check the repeatability of weld quality characteristics. The tensile samples were cut perpendicular to the direction of welding. The samples were prepared as per ASTM standard and were tested in universal testing machine. The ASTM D638 standard is shown in Fig. 5.

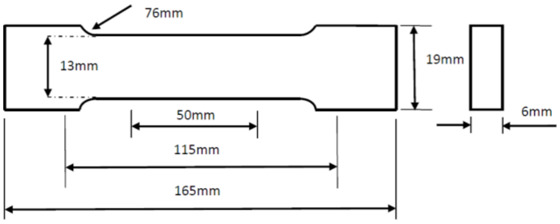

Fig. 5. Tensile specimen dimension

3. RESULT AND DISCUSSION

The top appearance of the weld bead profile was 750 rpm, 25 mm/min is shown in Fig. 7. It was observed that maximum tensile load is obtained at welding parameters rotational speed 750 rpm, 25 mm/min, 0.1 mm plunge depth and 2° tilt angle is 75.79 N (0.97 MPa) is shown in Fig. 6 the heat input plays an important role for the tensile strength of the joint. Increasing the rotational speed above 750 rpm leads to excess heat generation which leads to excess melting and thermal degradation of polypropylene whereas decreasing the rotational speed less than 750 rpm cause insufficient melting and mixing of the two materials. The low strength was due to improper mixing of polypropylene material with aluminum due to the formation of barrier by aluminum on the plastic side at both high RPM and low RPM. So to ensure proper mixing, using the same value of process parameters welding was performed for slot type where the polypropylene is inserted in the aluminum. It is observed that maximum tensile load obtained from the test is 120.79 N (1.54 MPa) which means there is increase from 75.79 to 120.79 N i.e. 62.8% in strength with respect to simple butt welding.

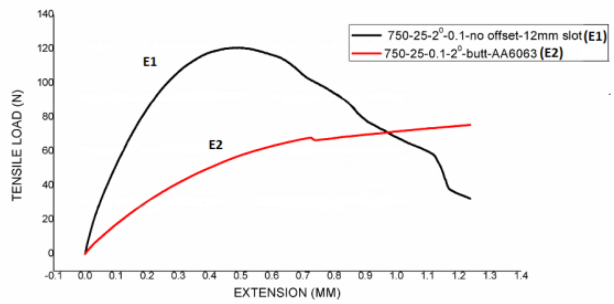

Fig. 6 Load (stress) vs Extension (strain) during tensile test

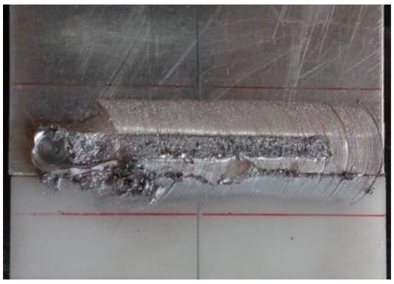

Fig. 7 Welded sample

3.1 Variation of Axial force with time in FSW process

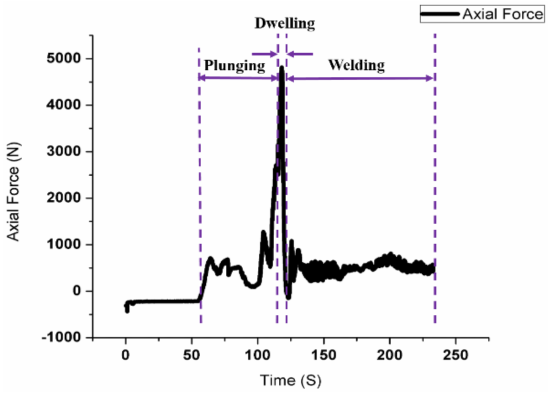

Fig. 8 Variation of Axial force with time during FSW(750 rpm, 25 mm/min)

Fig. 8 defines the typical axial force versus time plot for the entire welding process of slot type design where the polypropylene is inserted in the aluminum. The parameters considered is as follows: tool rotational speed 750 rpm, traverse speed 25 mm/min. The entire force signal is divided into mainly four phases. Firstly, during the plunging phase, when the tool pin comes in contact with the work piece, force starts to rise because the work piece is more or less cold and more load is required to penetrate the work piece material. The maximum force value is obtained at a point when the shoulder comes in direct contact with the work piece. The peak force value obtained during the whole process was about 4852 N. Secondly, during dwelling phase there is sudden decrease in value of force. Actually, the heat build's up in and around the tool and work piece. As a result deformation of material occurs and the material gets softened the material from the work-piece surface was removed in the form of fine particles. The time difference between the peak force value and the stage from which the force has become almost constant is nearly 15 seconds. This time is devoted for dwelling which is a fixed characteristic of the machine. In general, Thermoplastic materials are soft in nature with low binding energy. The intermolecular force of attraction between the particles of this material is low, which is significantly different from metallic structure. Therefore, the axial force decreased continuously. Finally, the welding phase started, where this force was found to be almost constant. During this stage, the little variation of axial force due to the shoulder rotation over the base plate surface. Lastly, the tool retracted out of the welded sample just after welding when the force dropped down due to disconnection from weld plates.

3.2 Temperature evolution

During friction stir welding, rotational speed and translational speed greatly influences the heat generation which directly affects the temperature. Increasing the rotational speed increases the heat generation. on the other hand, increasing traverse speed would decrease the plastic deformation and heat generation this is mostly due to short time duration available for spinning the work-piece to generate heat.

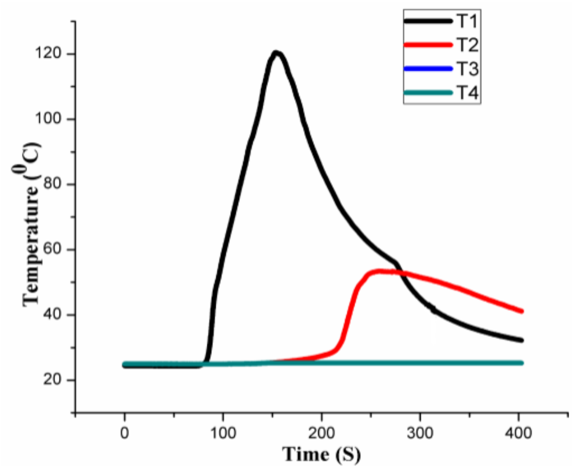

Fig. 9Thermal cycle at various distance from weld centerline in FSW (750rpm, 25 mm/min)

Four numbers of k-type thermocouples were placed, out of which two thermocouples (T1 and T2) are fixed on aluminum side at the distance of 30 mm from the starting point of the weld and other at a distance of 60 mm from the starting point. These thermocouples were placed at a distance of 13.5 mm and 16.5 mm from welding Centre line. Similar pattern was followed for the polypropylene side (T3 and T4).In graph the T3 and T4 signals overlapped to each other. During the experiment, the thermocouples' readings have been taken on both advancing side and retreating side at process parameters 750rpm, 25mm/min, 0.1mm and 2^0. When the tool plunging starts, the temperature in the first thermocouple rises rapidly and reaches a maximum of 120°C. But as the tool movement starts temperature decreases in first thermocouple and in second thermocouple temperature starts to increase until it reaches a maximum value of 60°C. When tool reaches that point**.** This variation could have prevailed due to various reasons like environmental effects, positioning of thermocouple. Thermocouples which were placed in polypropylene did not showed any response to temperature rise during welding. This variation could have prevailed due to various reasons like environmental effects, positioning of thermocouple. Referring to Fig. 9 thermocouples which were placed in polypropylene have shown negligible variation in the weld temperature. This can be attributed due to the low thermal conductivity and the low yield strength of plastic materials. Low thermal conductivity of plastic led to poor heat distribution in its heat affected zone. In addition to that, low of amount of frictional heat has been generated in plastic due to lower yield strength. Thus, poor thermal conductivity and low yield strength resulted in low frictional heat in plastic materials. Any response to temperature rise during welding because of its low thermal conductivity.

4. CONCLUSIONS

In the present research work, a traditional tool with a threaded cylindrical pin having shoulder diameter 25 mm, pin diameter 6 mm and pin length 5.6 mm was used to weld 6 mm thick aluminum and polypropylene sheets. Three different tool rotational speeds (400, 750, 1000 rpm) and tool traverse speeds (15, 25, 50 mm/min) were selected for the investigation. A constant tilt angle of 2° was also provided to the tool. Following conclusions are made from the experimental study-

- Tensile strength of the welded joints were lower compared to the base material of polypropylene due to improper mixing of polypropylene material with aluminum due to the formation of barrier by aluminum on the plastic side.
- Maximum tensile load of 120.79 N was obtained for rotational speed of 750 rpm, welding speed of 25 mm/min, plunge depth of 0.1 mm and tilt angle of 2°.
- The welding efficiency of below 10% w.r.t polypropylene has been found which is not adequate.
- Maximum peak temperature during welding is found to be 120°C which is lower than the melting temperatures of the polypropylene. So joining is pure solid state joining.
- In friction stir welding during plunging the force value increases suddenly and then during welding phase the force drops to a more stable steady state unlike metal forming processes

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