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Optimization of friction stir welding process parameters to maximize tensile strength of stir cast AA6061-T6/AlN_p composite

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Aluminium Matrix Composites (AMCs) reinforced with particulate form of reinforcement has replaced monolithic alloys in many engineering industries due to its superior mechanical properties and tailorable thermal and electrical properties. As aluminium nitride (AlN) has high specific strength, high thermal conductivity, high electrical resistivity, low dielectric constant, low coefficient of thermal expansion and good compatibility with aluminium alloy, Al/AlN composite is extensively used in electronic packaging industries. Joining of AMCs is unavoidable in many engineering applications. Friction Stir Welding (FSW) is one of the most suitable welding process to weld the AMCs reinforced with particulate form of ceramics without deteriorating its superior mechanical properties. An attempt has been made to develop regression models to predict the Ultimate Tensile Strength (UTS) and Percent Elongation (PE) of the friction stir welded AA6061 matrix composite reinforced with aluminium nitride particles (AlN_p) by correlating the significant parameters such as tool rotational speed, welding speed, axial force and percentage of AlN_p reinforcement in the AA6061 matrix. Statistical software SYSTAT 12 and statistical tools such as analysis of variance (ANOVA) and student's *t* test, have been used to validate the developed models. It was observed from the investigation that these factors independently influenced the UTS and PE of the friction stir welded composite joints. The developed regression models were optimized to maximize UTS of friction stir welded AA6061/AlN_p composite joints.

1. Introduction

AMCs reinforced with particulate form of reinforcements find extensive applications in sports equipment, automotive and aerospace industries due to its superior mechanical, thermal and tribological properties as compared with its corresponding monolithic alloys [1,2]. As those properties of AMCs are tailorable by changing the weight percentage of reinforcement in the matrix, their usage has enormously increased. AMCs reinforced with particulate form of ceramics are particularly attractive due to its isotropic properties, higher operating temperature, oxidation resistance, ease of fabrication over the other geometries of reinforcement such as flake and fiber [3]. To enhance the effective use of AMCs, secondary processes such as joining and machining are as equally significant as the fabrication of AMCs. Joining of AMCs by traditional fusion welding processes which are normally applied to Al alloys results in reduced joint strength due to oxide inclusions, solidification shrinkage, porosity, distortion, more residual stress, formation of intermetallic compounds due to chemical reactions between matrix and reinforcement, etc. [4]. Al alloy matrix heated to its melting point is the primary reason for the above said problems. If AMCs are welded by solid state welding process, these problems can be eliminated [4].

Friction stir welding is a low heat input solid state welding process invented by The Welding Institute, UK in 1991 [5]. A non-consumable rotating hard tool is used to plasticize the abutting surfaces of the plates to be joined by generating a frictional heat and to stir the plasticized material from the advancing side to the retreating side of the tool and consolidate at the retreating side by the axial force acting through the tool shoulder. A detailed description about the FSW process is presented in literature [6,7]. FSW was initially intended to weld aluminium based low melting point alloys. Due to the success of FSW process to weld Al alloys, FSW was used for other monolithic alloys such as magnesium and copper [8,9] and then extended to weld high melting point materials such as nickel, mildsteel and stainless steel [7,10–12]. For the past one decade, FSW has been successfully employed to

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weld advanced materials like AMCs reinforced with hard ceramics materials such as SiC, Al_2O_3, B_4C, TiB_2, TiC and ZrB_2 [13–18].

In the welding of AMCs, FSW process produces remarkable weld quality as compared to the weld produced by fusion welding process. In FSW process, reinforcement particles are not agglomerated in the weld zone as it gets agglomerated in the case of fusion welding process. Also reinforcement particles are distributed uniformly in the weld zone even though reinforcement particles are agglomerated in base material [19]. In addition to that, due to the dynamic recrystalization and reduction of Al matrix grain size in the weld zone by the intense stirring of material, mechanical properties of friction stir welded joints are comparable with those of base composite [14]. Joint efficiency of friction stir welded AMCs was reported above 95% under the optimized FSW process condition [17,18]. As FSW process produces superior weld quality under optimized process condition, currently it is successfully employed in many engineering fields such as aerospace, shipbuilding and military applications where high quality weld is required [20].

Among the various FSW process parameters such as tool rotational speed, welding speed, axial force, tool geometry, tool material, tool tilt angle, clamping force and geometry, the first four parameters play a significant role to produce sound weld joints. Tool rotational speed influences the temperature in the stir zone and subsequent grain growth [21]. Higher tool rotation rates generate higher frictional heat due to higher relative motion between the tool and substrate and result in more intense stirring and mixing of material [22]. The rate of stirring of plasticized material determines the formation of defects in the weld zone. Excessive stirring of plasticized material will result in tunnel defects. Lack of stirring will result in lack of bonding. Azimzadegan and Serajzadeh [23] observed an increase in the width of stir zone with increased tool rotational speed. The welding speed determines the exposure time of this frictional heat per unit length of weld and subsequently affects the grain growth [24]. The rate of heating in a thermal cycle during FSW is a strong function of the welding speed. Increase in welding speed causes a decrease in frictional heat generation and lack of stirring [25]. The welding speed also influences the width of the stir zone. The welding speed prompts the linear motion of tool which in turn moves the plasticized material from the front to the back of the tool pin and completes the welding.

As the axial force increases, both hydrostatic pressure beneath the shoulder and the temperature in the stir zone will increase. The hydrostatic pressure should be higher than the flow stress of the materials to be welded. Axial force is also responsible for flash formation. An excessive axial force results in higher amount of flash leading to defects [26]. The shoulder force is directly responsible for the plunge depth of the tool pin into the substrate [27]. FSW tool geometry is another significant parameter to influence the material flow and weld joint properties. Material flow is predominantly influenced by the FSW tool profiles, FSW tool dimensions and FSW process parameters [25]. The FSW tool is harder than the material to be welded. The tool plays the following three major roles in the formation of the joint [28]: (1) Generate the frictional heat beneath the shoulder. (2) Extrude the plasticized material from the front to the back of the tool pin and, (3) forge the plasticized materials by its shoulder. The formation of various regions of friction stir welded joint is affected by the material flow behavior under the action of rotating non-consumable tool.

Some of the tool pin profiles analyzed by the researchers are straight and draft type of cylindrical, square, triangular, hexagonal, octagonal and cylindrical threaded. Elangovan and Balasubramanian [25] attempted to weld AA2219 aluminium alloys by various profile tool pins such as straight cylindrical, taper cylindrical, threaded cylindrical, straight square and straight triangular. It was found that straight square profile pin gave better tensile strength among the other tool pins. Vijay and Murugan [29] developed the different FSW tool pin profiles viz., straight square, straight hexagon, straight octagon, taper square, taper hexagon and taper octagon with different shoulder to pin diameter (D/d) ratio of 2.8, 3 and 3.2 to weld the in situ Al-6061-10 wt% TiB_2 composite and studied the effect of tool pin profile on metallurgical and mechanical properties of the weldments. It was found that straight square profile tool pin with the D/d ratio of 2.8 exhibited better joint strength with fine grains at the weld zone when compared to the other pin profiles.

From the literature of FSW of AMCs [17,18] it is evident that joint strength of friction stir welded composite is highly influenced by percentage of reinforcement in the composite. Fogagnolo et al. [30] studied the UTS of Al matrix composites reinforced with 5 wt% AlN and 15 wt% AlN produced by mixing the Al and AlN powder by two process namely (a) conventional mixing and (b) mechanically alloying and then these powder mixtures were consolidated by cold-pressing followed by hot extrusion. Surprisingly, UTS of composite containing 15% AlN was less than that of composite containing 5% AlN produced by both the processes. It was justified that sharp angles and cracks usually present in the particulate reinforcements and agglomeration of reinforcement increased the stress concentration and affected the UTS. In higher reinforcement (15 wt% AlN) composite, possibilities of above defects were more as compared to the composite containing less reinforcement (5 wt% AlN). Hence in this study, percentage of reinforcement was also taken as a parameter to obtain the maximum UTS of the composite. Al/SiC and Al/AlN composites are extensively used as electronic packaging materials [31]. Even though the thermal conductivity of AlN (175 W/m K) is less than SiC (250 W/m K), AlN is chemically more stable than SiC at higher temperatures. Aluminium does not react with AlN [31] whereas in Al/SiC composites, Al reacts with SiC and forms brittle Al_4C_3 phase which deteriorates the mechanical properties of Al/SiC composite [32].

In the present work, an attempt has been made to join the AA6061/AlN_p composite by FSW process. The four factor, five level central composite rotatable design matrix was adopted to carryout the experiments to reduce the number of experimental runs. Two regression models were developed to correlate the significant parameters such as tool rotational speed, welding speed, axial force and percentage of reinforcement with the UTS and PE of friction stir welded AA6061/AlN_p composite. The developed regression models have been optimized by using the generalized reduced gradient method to attain the maximum UTS in three different situations as follows: (i) maximizing the UTS, (ii) maximizing the UTS at higher welding speed and (iii) maximizing the UTS and PE at higher welding speed.

2. Scheme of investigation

2.1. Production of AA6061/AlN_p composite

AA6061/AlN_p composite was produced by stir casting technique. An indigenously developed modified electric stir casting furnace with bottom pouring arrangement was used to fabricate the composite. Cleaned extruded aluminium alloy (AA6061-T6) rods of 25 mm diameter were loaded inside the coated stainless steel crucible and the temperature of the electric furnace was set to 1000 °C. The chemical composition of AA6061 alloy is presented in Table 1. The melt was stirred by a coated stainless steel stirrer coupled with electric motor to facilitate both incorporation and uniform distribution of the AlN_p reinforcement in the molten Al alloy. The crucible and stirrer were coated to avoid any contamination at higher temperature. A predetermined quantity of preheated AlN_p of size 3–4 μm was added into the melt at the side of the vortex. To increase