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A review of tool wear prediction during friction stir welding of aluminium matrix composite

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Abstract: Friction stir welding is the preferred joining method for aluminium matrix composites. It is a solid-state process which prevents the formation of the intermetallic precipitates responsible for degradation of mechanical properties in fusion welds of these composites. The major concern in friction stir welding is the wear of the welding tool pin. The wear is due to the prolonged contact between the tool and the harder reinforcements in the composite materials. This paper provides an overview of the effects of different parameters of friction stir welding on the tool wear. It was found that the total amount of material removed from the tool is in direct proportion to the rotational speed of the tool and the length of the weld but inversely proportional to the transverse rate. The results even demonstrate that the tool geometry also has significant influence on the wear resistance of the tool. The tool even converts itself into a self-optimized shape to minimize its wear.

Key words: friction stir welding; aluminium matrix composites; tool wear

1 Introduction

Particulates reinforced aluminium matrix composites (AMC) are considered as one of the most promising structural materials for advanced applications in aerospace, military and transportation industries [1]. However, in order to produce larger or more complex structural components, it is inevitable to join AMCs to themselves or other materials. Therefore, some joining processes such as fusion welding [2−4], brazing [5] and diffusion bonding [6−8] were developed, but they resulted, to different extent, in the degradation of mechanical properties. Friction stir welding (FSW) is considered as a prospective joining process to solve this problem. As a solid-state joining process, FSW can eliminate the welding defects associated with fusion welding processes [9]. During FSW, the joining of plates takes place below the melting point of the materials. The maximum temperature reached during the process is 80% of the melting temperature of the work pieces. The welds are created by the combined action of frictional heating and mechanical deformation due to a rotating tool. The detrimental effects of arc welding such as distortion and residual stresses are due to the rapid heating beyond the melting temperature and cooling of the joints. These detrimental effects are minimized in FSW, as the heat generated is not severe enough [10].

1.1 FSW process

FSW is a joining technique developed by The Welding Institute (TWI) of Cambridge, England, in 1991 [11]. In FSW, a cylindrical, shouldered tool with a profiled probe, shown in Fig. 1, is rotated and slowly plunged into the joint line between two pieces butted. FSW process with a schematic diagram is shown in Fig. 2. The parts have to be clamped onto a backing bar in a manner that prevents the abutting joint faces from being forced apart. The tool serves two primary functions: heating of work piece, and movement of material to produce the joint. Contact of the pin with the work piece creates frictional and deformational heating and softens the work piece material; contacting the shoulder to the work piece increases the work piece heating, expands the zone of softened material, and constrains the deformed material [14]. The plasticized material is transferred from the leading edge of the tool to the trailing edge of the tool probe and is forged by the intimate contact of the tool shoulder and the pin profile. As a result of this process, a joint is produced in “solid state” [13].

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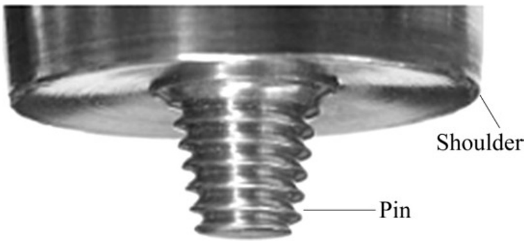

Fig. 1 Parts of FSW tool [12]

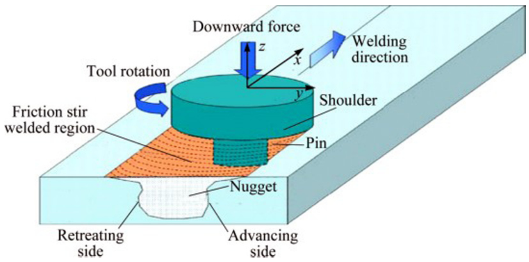

Fig. 2 Schematic drawing of FSW [13]

According to the microstructural evolutions, there are three zones in the welding zone: stirring zone (SZ), heat-affected zone (HAZ) and thermo-mechanical affected zone (TMAZ) [15−18]. SZ is characterized by fine and equiaxed grains. TMAZ includes elongated and recovered grains. But, HAZ is identified only by the hardness result because there is no obvious difference in grain structure compared to the base metal [19]. The onion rings formed in the stirring zone is found to be the results of the combination of the slight grain size variations and a change in nature and size of the particles, i.e., intra vs intergranular [20]. One of the major benefits of FSW is that it has significantly fewer process elements to control as compared to fusion weld which is controlled by purge gas, voltage, wire feed, traverse speed, shield gas and arc gap. The increase in joint strength combined with the reduction in process variability provides an increased safety margin and high degree of reliability [21].

It is well known that the main challenge in any of the welding process for the manufacturer is to select the optimum welding parameters which would produce an excellent welded joint [22]. FSW process is controlled by rotational speed, welding or transverse speed, axial force, tool geometry and tool tilt angle. The tool geometry includes pin length, pin diameter, tool shoulder diameter, ratio of tool shoulder diameter and pin diameter of the tool [23].

The rotational speed helps in stirring, mixing of material and generating the frictional heat, transverse speed controls the heat as well as reason of appearance of weld generated, axial force helps in maintaining contact conditions and generates the frictional heat and the tilting angle helps in thinning and appearance of the weld. Further, the plunge depth of pin into the work pieces (also called target depth) is important for producing sound welds with smooth tool shoulders. The welding speed prompts the translation of tool which in turn pushes the stirred material which arises due to the tool rotation from front to the back of the tool pin and completes the welding. The rubbing of tool shoulder and pin with the work piece generates the frictional heat [24]. Working range of each parameter is decided upon by inspecting macrostructure (cross section of weld region) for a smooth appearance without any visible defects such as pinhole, tunnel defect, crack, void, surface groove and surface galling. It has been observed that when tool rotation speed is lower than 1000 r/min, tunnel defect is at the middle of retreating side of weld region which may be due to insufficient heat generation and insufficient metal transportation. When tool rotation speed is higher than 1400 r/min, tunnel defect is observed at the top of retreating side which may be due to excess turbulence caused by higher tool rotation speed. When welding speed is lower than 22 mm/min, tunnel defect is observed at retreating side due to excess heat input per unit length of weld. When welding speed is higher than 75 mm/min, tunnel at retreating side and middle of weld region is observed due to inadequate flow of material causes by insufficient heat input. When axial force is lower than 2 kN, pin hole defect at retreating side is observed due to the absence of vertical flow of material caused by insufficient axial force. When axial force is increased beyond 4 kN, it results in tunnel defect at both sides of retreating and advancing and excessive thinning due to higher heat input [25]. A fully coupled thermo-mechanical model is adopted to study the effect of shoulder size on the temperature distributions and the material deformations in FSW. Numerical results indicate that the maximum temperature can be increased with the increase of the shoulder diameter. The stirring zone can be enlarged by the increase of the shoulder size [26]. It is observed that increasing rotational (ω) and traverse speed (v) ratio increases the weld nugget size and decreases the incomplete root penetration. By increasing ω/v ratio, a slight decrease in the effective tensile properties calculated from shear punch test (SPT) of different zones is observed. That is due to increased heat input and softening of the material in these regions. Furthermore, increasing ω/v ratio results in the formation of a larger weld nugget due to an increase in heat input and an easier material flow. Therefore, the probability of formation of “incomplete root penetration” defect is reduced with increase in ω/v ratio [27].

1.2 Joining of AMC

AMCs have received considerable attention over the past 30 years due to their significant properties.