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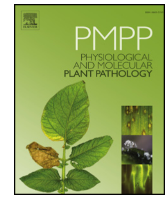

Influence of ridges shoulder with polygonal pins on material flow and friction stir weld characteristics of 6082 aluminum alloy

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A R T I C L E I N F O

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A B S T R A C T

In the present paper, the flow of stirred material under ridges shoulder combined with various polygonal pin profiles during friction stir welding (FSW) of 6082 aluminum alloy was investigated through marker insert technique. The marker inserts (copper) were placed in 'parallel to/along the weld' and 'perpendicular to weld configurations'. The axial force and tool torque during the welding were measured and compared for all the tools. Final weldments were subjected to radiographic and sectioned macro and microscopic observation to understand the detailed flow of marker material. The results show that the material driven by pin moves from bottom to top which improves the flow in the top layer of material i.e., shoulder region. The individual effect of pin profiles on material flow was clarified. The welds with square pin tool, $(T_R)_S$ resulted in superior mechanical properties and uniform weld zone hardness with complete mixing and distribution of material on both advancing side (AS) and retreating side (RS).

1. Introduction

Friction stir butt welding (FSW) has emerged as a most promising solid-state joining technique, mainly for aluminum and its alloys some of which were earlier considered as un-wieldable [1,4]. The tremendous growth of FSW has increased its applications after its invention in 1991 at The Welding Institute (TWI), Cambridge [2]. FSW facilitates joining of various similar and dissimilar material combinations such as Al-Ti, Al-SS, and Al-Cu etc. [3].

The FSW process occurs in simple three steps: plunging, dwelling, and welding. In plunging phase a non-consumable tool with a typical design was rotated at desired rotational speed and inserted in to the rigidly clamped workpieces at the welding line up to desired plunge depth i.e. until the tool shoulder touches the workpieces. In the dwelling phase, the rotating tool was allowed for certain time to generate frictional heating at the tool shoulder interface thereby softening the surrounding. In the last phase, the rotating tool was traversed along the welding line with desired welding speed to form the joint between the two plates [4]. The quality of the friction stir welds depends completely on the processing parameters and tool geometry. Even though the processing parameters play a key role in the heat generation, the plastic deformation was mainly altered by changing the tool geometry. The interacting part of tool essentially comprises of two components: shoulder and pin. The shoulder was mainly responsible for the contact frictional heat whereas the pin was responsible for shearing and transporting the material from leading edge (LE) to the trailing edge (TE) of the weld [5].

The shoulder was responsible for major heat contribution. Hence, to improve the joint properties and minimizing the defects the concept of shoulder designs emerged. The plane, concave and convex shoulder designs were widely adopted tool designs for which considerable research was carried out by many researchers [6–9].

Galvao et al. [6] investigated the effect of various shoulder features on 1 mm thick copper sheets and noticed that the scrolled shoulder generates more heat, finer grains, and higher hardness compared to flat and concave shoulder profiles. In a similar study, Cederqvist et al. [7] investigated the effect of convex, concave and flat tool geometries with multiple weld cycles on the stability of welds during welding of 5 mm thick copper sheets. They observed that the welds with convex tool shoulder geometry resulted in the minimum amount of flash and defect free when compared to the welds with concave and flat scroll tool shoulder geometries. The attempts of Scialpi et al. [8] on various shoulders during 6082 friction stir welds shown a significant change in the heat input and weld zone dimensions. Further, Leal et al. [9] thoroughly investigated the used of scrolled feature and observed that the dragging of material in to the feature supports its mixing and downward motion around the pin as compared to conical shoulder.

Few authors have studied the tool pin influence on the mechanical properties of the weld [10–18].

Elangovan et al. [10] studied the influence of tool pin profile on the

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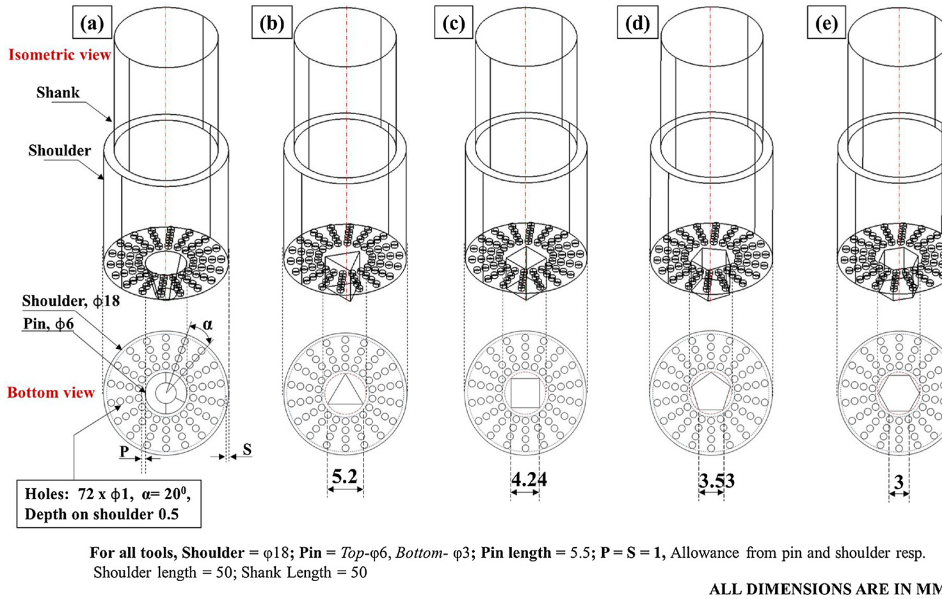

Fig. 1. Tools used during FSW process: Ridges shoulder with (a) Taper cylindrical (T_R) (b) Triangular $(T_R)_T$ (c) Square $(T_R)_S$ (d) Pentagon $(T_R)_P$ and (e) Hexagon $(T_R)_H$ tool pin profiles.

quality of friction stir welded Al 6061 alloy and observed that because of the eccentricity associated with the tool pins (polygonal pins) the material which is incompressible was allowed to pass around the pin profile. They also observed that the polygonal (square) pin profiled tool resulted in better properties compared to other tools. In another attempt Balasubramanian et al. [11] studied the effect of pin profile on the mechanical properties of the weld and understood that the joints fabricated with the square tool pin profile achieved better properties when compared to the other tool pins. The study conducted by Biswas et al. [12] on the effect of tool geometry revealed that the geometry of the pin plays a key role only in the material deformation and moreover the heat generation developed by the pin was relatively insignificant to the weld. Khodaverdizadeh et al. [13] investigated with copper friction stir welds using and threaded and square tool pin and found that due to the eccentricity action of the edges, the tool pin with square resulted in finer grains thus lead to superior properties compared to conical tool pin profile. The investigation of Imam et al. [14] during the friction stir welding of Al 6063 alloys with different tool pins showed that the tapered circular and polygonal pins result in defects compared to square tool pin. The welds with square tool pin profile achieved superior mechanical properties compared to other tool pins. The attempts by Mehta et al. [15] to study the adhesion of plasticized material in polygonal tool pin profiles showed that at higher weld pitch (traverse speed up on rotational speed) the pins with less number of sides avoids permanent adhesion and the stresses were observed to be low for pins with larger number of sides. They developed a relation for obtaining the optimum sides of the polygon pin for a given set of FSW conditions and it was related to the weld pitch. In a similar attempt, Mehta et al. [16] used the polygonal tool pins which have the capability to improve the mechanical strength of the joint compared to circular pin tools and analyzed the sticking torque experienced by the polygonal pins along with the rate of heat generation. It was noticed that with an increase in the number of sides, the rate of frictional heat generation increases along the pin vertical and bottom surfaces. The traverse force was observed to be decreasing with increasing the number of sides and maintains steady tool torque.

Rao et al. [17] experimented on Al 2219 friction stir welds with triangular and conical pin profiles and understood that the welds with triangular pin profile resulted with finer grains compared to the welds with conical tool pin. They found that the shape and geometry of the welding tool were completely dependent on the geometry of the tool pin and not on the welding conditions. Amirafshar et al. [18] observed that the lower grain size is achieved with the polygonal (square) tool pin profile compared with the conical, cylindrical and triangular pin profiles.

Mugada et al. [19] studied the role of shoulder end feature on temperature generation around the tool shoulder periphery and observed that the shoulder feature facilitates additional flow of material, and generates higher temperature compared to flat/featureless tool.

Considerable research work has been carried out addressing the efficient use of individual tool shoulder profiles and pin profiles respectively. However, the combined shoulder and pin design effects on material flow and weld quality were not addressed. Therefore, in the present paper, the influence of specific ridges shoulder end feature with the polygon pin profiles on the material flow, macrostructure and mechanical properties of the welds have been investigated during FSW of 6082 aluminum alloy.

2. Materials and methods

The 6082 aluminum alloy sheet of 0.96%Mg, 1.16%Si, 0.54%Mn, 0.025%Cu, 0.048% Zn, 0.02% Cr, 0.009%Ti and remaining 96.92% Al with dimensions 280 mm × 70 mm × 6 mm in T6 heat treated condition was chosen as the workpiece material. The suitable tool material for welding aluminum and its alloys was identified as H13 tool steel from the literature work [4]. The as received H13 tool steel is having a hardness of 30-45 HRC and was subjected to different heat treatment cycles such as re-heating, annealing, solution-zing and aging, as a result, the hardness was improved to 50-55HRC. The ridges shoulder end featured tools with different polygonal pin profiles used during the FSW process were shown in Fig. 1. Based on trial and error experiments, the process parameters were selected and listed in Table 1. The FSW experiments were performed on the numerically controlled 3 ton friction stir welding machine Model: FSW-3T and manufactured by RV Machine tools, Coimbatore with inbuilt data acquisition of force and torque. In order to gain information about the overall material transport and flow variations through the thickness of the plate, marker (copper) inserts of 0.25 mm thick were inserted by cutting the narrow slots into the faying surface with Wire-Cut EDM and press fitting the markers into the slot at different positions i.e., at “perpendicular to the weld line” and “parallel or along the weld line” as shown in Fig. 2. The marker flow was elucidated by performing the radiography of the weldments.