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Effect of small tool pin profiles on microstructures and mechanical properties of 6061 aluminum alloy by friction stir welding

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Abstract: The effect of small tool pin profiles on the microstructures and mechanical properties of 6061 aluminum alloy joints using friction stir welding (FSW) technique was investigated. Three different tool pin profiles: threaded tapered cylindrical (T_1), triangular (T_2) and square (T_3) were used to produce the joints. The results indicate that the weld joints are notably affected by joining with different tool pin profiles. The triangular tool pin profile produces the best metallurgical and mechanical weld properties compared with other tool pin profiles. Besides, the lowest tensile strength and microhardness are obtained for the joint friction stir welded with square tool pin profile. It is observed that the smaller tool pin profile and shoulder diameter lead to narrow region of heat affected zone (HAZ) and a desired level of softening. The fracture surface examination shows that the joints are also affected when welding with different types of tool pin profiles. The fracture surface shows that the triangular specimen fails with a ductile fracture mode during the tensile test, while the brittle fracture modes are observed in the joints fabricated with other tool pin profiles (T_1 and T_3).
Key words: friction stir welding; small tool pin profile; mechanical properties; aluminum alloy; grain size

1 Introduction

Friction stir welding (FSW) is a solid state welding process in which the relative motion between the welding tool and the workpieces produces heat. This makes the material soft, and therefore it can be joined by plastic deformation diffusion. This method relies on the direct conversion of mechanical energy to thermal energy forming the weld joint without any external source of heat [1]. In the FSW process, a non-consumable rotating tool is forced down into the joint line under conditions where the frictional heating is sufficient to raise the temperature of the workpieces. It can plastically deform and locally plasticize. In the FSW technique, there is no liquid state of the material, and the weld takes place in the solid phase under the melting point of the material [2]. Thus, all the problems related to the solidification of a fused material are avoided.

Tool pin profile is a very important factor for producing sound and defect free welds. The optimization of FSW tool pin geometry plays an active role in increasing the quality of the weld [3]. During this process, the material undergoes an intense plastic deformation at elevated temperature, resulting in a significant grain refinement in the nugget zone (NZ). This phenomenon is known as dynamic recrystallization [4]. The tool geometry, in particular the pin profile, is a predominant factor in determining the weld geometry, localized heating, and stirring action. However, the behaviour of material flow is predominantly influenced by the tool pin profile, tool pin dimensions and FSW process parameters [5]. ELANGOVAN et al [6] studied the influences of tool pin profile and welding speed on the behaviour of material flow and the quality of the weld. They reported that the tool pin profile plays a major role in deciding the quality of the weld. However, very little attention has been paid to the effect of pin profile on the distribution of particles [7, 8].

The grain refinement by FSW in alloys has been reported by several researchers [9−15]. It has been demonstrated that the grain structures depend heavily on the processing conditions, including processing parameters, tool geometry and cooling rate. However, a

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recent research has also uncovered several complexities and special features of the material flow in FSW such as the lack of mixing the plasticized materials on atomic scale and the formation of certain interesting patterns which still require further work. Besides, no effort has been devoted to study the effects of small tool pin profiles on the NZ formation. Accordingly, the objective of this study is to investigate the effect of small tool pin profiles and small unchanged shoulder diameter on the microstructures and mechanical properties of 6061 aluminum alloy joints. Moreover, small pin dimensions are recommended to fabricate a weld joint which has a plate thickness of 4 mm or less, because the plate thicknesses more than 4 mm lead to break pins.

2 Experimental

6061 aluminum alloy was used with the chemical composition: 97.57% Al, 0.525% Si, 0.339% Fe, 1.062% Mg, 0.120% Cu and 0.080% Mn. The material was supplied by a local supplier (Heap Sing Huat Metal and Machinery Sdn Bhd). The aluminum plate with a thickness of 4 mm was sliced into the required sizes (210 mm × 100 mm) using a cutting band saw machine (UE−712A). Three pairs of aluminum alloy strip were coupled in a butt joint configuration paralleling to the rolling direction of the plates and clamped rigidly on the backing plate. Before the FSW process, the surfaces of plates were cleaned using acetone to remove the dirt and grease.

The FSW was carried out on a vertical milling machine, type KAMA (X6325; 3Hp; TRPER R8; 30 KN). The axial force was measured using a load cell and found approximately equal to 7.5 kN. The FSW tools were designed and manufactured from medium carbon steel and were heat-treated to about HRC 58. The chemical composition of the welding tool is shown in Table 1. Three FSW tools with different pin geometries denoted as T_1, T_2 and T_3 were employed, and the profiles are shown in Fig. 1. The T_1, T_2, and T_3 pin were inscribed in a circle with a diameter of 2 mm and each tool pin had a length of 3.7 mm. A tool shoulder had a diameter of 9 mm. The welding tool rotated in a clockwise direction at a constant rotational speed of 1750 r/min. The rotating tool traversed at a speed of 60 mm/min along the weld line perpendicular to the rolling direction. However, these values for traverse and rotation speeds were considered to be the best parameters obtained experimentally during the FSW process. The single pass welding procedure was followed to fabricate the joints. The FSW produced an asymmetric microstructure representing the advancing side (AS) and retreating side (RS). The AS is the side in which the velocity vector of rotational speed is in the same direction with the welding speed and the other side represents the RS.

Table 1 Chemical composition of welding tool (mass fraction, %)

C	Mn	P	Fe
0.44	0.79	0.012	Bal.

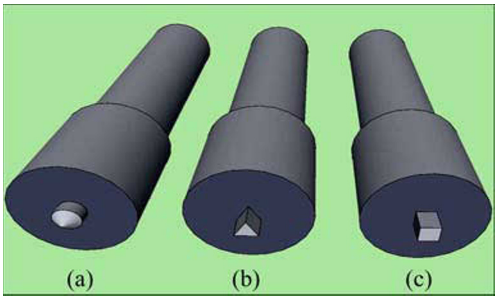

Fig. 1 Tool pin geometries: (a) Threaded tapered cylindrical pin T_1, (b) Triangular pin T_2; (c) Square pin T_3

Four welds were fabricated for each parameter test in order to ensure the accuracy and repeatability of results. The best possible welded sample was then selected from each parameter test-set based on the criteria of visual inspection to evaluate the welds. A continuous and visual defect free weld seam was required. Three specimens of each weld, from the beginning, middle, and end of the weld, were considered for each mechanical test.

A microstructural analysis was performed on the cross section perpendicular to the welding direction. The specimens for metallographic examination were sectioned to the required sizes and ground to a smooth surface using different abrasive papers (180−1500). The final polishing was performed using the diamond paste solution with the particle size of 0.5 μm. The microstructure of specimens was revealed through inundation etching in Keller's reagent (2 mL HF + 5 mL HNO_3 + 3 mL HCl + 190 mL H_2O). The microstructure of the specimens was examined by field emission scanning electron microscopy (FESEM) (ZEISS SUPRA 35VP). The welding samples of 6061 aluminum alloy were also analyzed using a D8 Advance X-ray diffractometer (Bruker Analytical X-ray Systems), using a copper target to identify the phases in the welded joints. For the tensile tests, the FSW plates were machined according to ASTM: E8/E8M−11 perpendicularly to the welding direction. The tensile testing was carried out on an INSTRON (universal testing machine) and loaded at 1 kN at room temperature. The Vickers hardness tests were conducted on a Vickers microhardness tester (FV−700E) in the plane along the direction perpendicular to the welding line. The indenter load was 9.8 N and the loading time was 15 s. The microhardness measurements enclosed the heat affected zone (HAZ), thermomechanically affected zone (TMAZ),