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Influence of tool geometry and rotational speed on mechanical properties and defect formation in friction stir lap welded 5456 aluminum alloy sheets

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ABSTRACT

Friction stir welding of AA5456 aluminum alloy in lap joint configuration is with two different tempers, T321 and O, and different thicknesses, 5 mm and 2.5 mm was investigated. The influences of tool geometry and various rotational speeds on macrostructure, microstructure and joint strength are presented. Specifically, four different tool pin profiles (a conical thread pin, a cylindrical–conical thread pin, a stepped conical thread pin and Flared Triflute pin tool) and two rotational speeds, 600 and 800 rpm, were used. The results indicated that, tool geometry influences significantly material flow in the nugget zone and accordingly control the weld mechanical properties. Of particular interest is the stepped conical threaded pin, which is introduced for the first time in the present investigation. Scanning electron microscopy investigation of the fracture location of samples was carried out and the findings correlated with tool geometry features and their influences on material flow and tension test results. The optimum microstructure and mechanical properties were obtained for the joints produced with the stepped conical thread pin profile and rotational speed of 600 rpm. The characteristics of the nugget zone microstructure, hooking height, and fracture location of the weld joints were used as criteria to quantify the influence of processing conditions on joint performance and integrity. The results are interpreted in the framework of physical metallurgy properties and compared with published literature.

1. Introduction

Lap joints are widely used in the assembly of parts and products in the transportation industry. Common examples include ship decks, railway tankers and goods wagons, and stringer to skin in aircraft fuselages. For these applications, panels are often straightened with stringers and profiles, which are mechanically or fusion welded joined in a typical lap joint configuration [1,2]. Friction stir welding (FSW) is an alternative joining process, which has several benefits when compared with mechanical or fusion welding, mainly with regard to the welding of aluminum alloys. Specifically, FSW is a solid-state process where the maximum process temperature does not reach the melting point of the welded materials. Thus, difficulties related to the sensitivity to solidification cracking and the formation of gas porosity, which are very common in fusion welding processes; do not occur in FSW [3,4]. On the other hand, as it does not require the use of rivets, as in mechanical joining, it results in lower weight for the component and shorter manufacturing times [4].

The process, patented in 1991 by The Welding Institute (TWI), is based on the use of a specially designed rotating tool, characterized by a shoulder and a shaped pin at its end, which is inserted into the adjoining edges of the materials to be joined. The heat flux generated by the combined frictional forces of the rotating shoulder pin and the imposed forge force, plasticize the material beneath the shoulder and moves it around the joint line and the shoulder. In this context, the proper selection of the height and the shape of the pin, (tool geometry), rotating speed and feed rate become critical parameters in optimizing the FSW process [2–4]. Among the above parameters, tool geometry can be considered as the most influential process parameter in heat generation and material mixing [5]. The variations in tool design are extensive and combinations of shoulder diameter, shoulder profile, pin length, pin diameter and profile, are all important parameters in determining other welding parameters such as rotational and tool advance speeds as well as the quality of the finished weld. Another important parameter in the determination of the suitability of a tool for a particular application

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is the tool material itself. Welding is carried out around 70–90% of the base material melting point so it is important that the tool material possess sufficient strength at these temperatures to avoid intense wear or fracture during the FSW process [5].

Because of the important role played by tool geometry in process optimization of FSW, a large number of studies have been reported in the literature on the effect of tool geometry on microstructure evolution and mechanical properties [6–14]. Of particular interest, is the work of Fujii et al. [7] on the effect of tool shape on mechanical and microstructural properties of friction stir welded 1050-H24, 6061-T6, and 5083-O aluminum plates. Although, these studies cover many aluminum alloy series and temper conditions; however, they are mostly limited to butt weld configurations and little has been reported on lap weld configurations and even less for variable thickness and dissimilar temper conditions, which are encountered in industry.

A characteristic feature of friction stir welds in lap mode configuration is the formation of a geometrical defect, called ‘hook’, originating at the interface of the two welded sheets. During welding, hook(s) could form because of the upward bending of the sheet interface due to the penetration of the tool into the bottom sheet and the concomitant upward movement of the material from the lower sheet to the upper one [15]. Ideally, the oxide film present at the surface of the material should be broken into small and dispersed particles, by the stirring movement of the tool. However, depending on processing conditions, this may not occur and a nearly continuous film of oxides may remain in the intermediate region between the upper and lower sheets. The presence of this defect will prevent the metallurgical bonding and reduce the mechanical properties of the joint. It is clear that, the tool shape significantly affects the hook geometry, which in turn impacts the failure mode and therefore the failure load of friction stir lap welds. Hence, in order to optimize the FSW process of lap welds, it is necessary to develop a better understanding of the formation of the hook defect and the impact of tool geometry on its generation and elimination [16–18].

In the present paper, some of the results related to the influence of tool geometry and rotational speed on defect generation in lap welded AA5456 sheets with different thicknesses and temper conditions are presented. The evolution of the microstructure and mechanical properties as a function of process parameters is studied and the optimum processing conditions are identified. The fracture surface of the failed joints are analyzed by electron microscopy and the microstructural constituents responsible for the degradation of mechanical properties are identified.

2. Experimental procedures

The investigated material was AA 5456 alloy. The material was received in the form of 1200 mm long and 500 mm wide plates. One of them was 5 mm thick and in T321 temper condition (cold worked) and the other one 2.5 mm thick in O condition (annealed). The chemical composition and mechanical properties of the material for the two conditions are indicated in Tables 1 and 2 respectively. Specimens 250 × 250 mm^2 in dimensions were machined from the as-received sheets with their end surfaces machined along the specimen length. The test pieces were first ground using steel brush and sandpaper to remove the oxide films, and then cleaned with acetone to remove any organic residues such as oil. To carry out FSW process, the coupons were fixed on a support plate, which had been fixed on the backing plate of the FSW machine.

Table 1
Chemical compositions of aluminum alloys.

Type	Chemical composition in wt.%					
	Al	Mg	Mn	Cu	Fe	Si
5456-T321	Bal	4.81	0.63	0.01	0.20	0.08
5456-O	Bal	4.79	0.50	0.02	0.18	0.12

Table 2
Mechanical properties of aluminum alloys.

Type	Failure load (N)	Elongation (%)	Hardness at 200 g load (HV)
Base plate 2.5 mm	21,250	35	89
Base plate 5 mm	50,500	16	140

The specimens were mounted in lap mode in the configuration shown in Fig. 1. All the welds were produced in such a way that the advancing side of the probe was always located near the top sheet edge (ANE). The thinner plate was placed below with an overlap width of approximately 50 mm.

In this study, four different friction stir welding tools were designed and manufactured. A schematic of their geometry and their dimensions are shown in Fig. 2. Tool geometries similar to T1, T2, and T4 have already been used in the literature [5,6,9]; however, in the present research all the tools have threads on their outer surface, which is a new feature. To the knowledge of the authors, the geometry used for the T3 tool is new and has not been previously reported. The shoulder diameter for all four tools was 20 mm and the pin length 7 mm corresponding to the intended lap welding depth. The shoulder underside surface was flat and the tilting angle of the probe tool was 3° for all the experiments. Both the shoulder and probe were made of H13 steel to insure pin dimensional stability during the FSW process. The welding direction was perpendicular to the rolling direction of the work piece and all the lap joints were welded using a travel speed of 30 mm/min and rotational speeds of 600 and 800 rpm.

After welding, three tensile shear specimens were wire cut perpendicular to welding direction according to AWS D17.3M:200X standard [19]. This provided samples with a specimen width of 25.4 mm and an overall joint length of approximately 250 mm. To balance the offset axes of the lap specimens and minimize bending effects, two packing pieces with the corresponding thicknesses (5 mm and 2.5 mm) were used during the tensile shear testing. The transverse tension tests were performed in a 500 kN capacity servo hydraulic tensile testing machine equipped with side entry hydraulic grips at a speed of 2 mm min^{-1}. For each tensile shear test specimen, the failure load and fracture locations were recorded. Macrostructural investigation and microstructural studies were carried out using optical microscope and SEM (Scanning electron microscope) equipped with an energy-dispersive X-ray analysis (EDX) system. For microstructural studies, samples were cut and polished according to standard metallographic techniques. They were all etched using a solution composed of 35 ml HNO_3, and 65 ml H_2O under warm conditions.

3. Results and discussion

3.1. Effect of pin geometry on the macrostructure of FSW joint

Pin profile plays a crucial role in material flow and in turn regulates the welding speed of the FSW process. Pin geometry

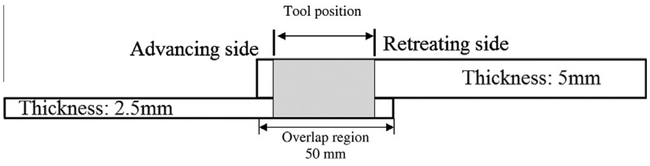

Fig. 1. Schematic of lap mode.