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An experimental investigation of torque and force generation for varying tool tilt angles and their effects on microstructure and mechanical properties: Friction stir welding of AA 6061-T6

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A B S T R A C T

Friction stir welding (FSW) has evolved as a very promising joining process for light weight material fabrication. Weld characteristics of FSW AA6061-T6 samples in terms of mechanical properties of weldment have been studied by varying the tool tilt angles for taper and taper threaded tool. Torque and different forces (Z force, X force) generated at the tool-workpiece interface are experimentally measured and analyzed to assess the effect of tilt angles. It is observed that torque and forces associated with FSW increases as tilt angle increase. Torque and vertical force (Z force) attained by the taper threaded tool is higher than that of taper tool whereas welding force (X force) for taper threaded tool is found to be less compared to taper tool. Fluctuation of welding force increases with increase in tilt angle for taper tool but taper threaded tool exhibits an opposite behavior. The onion ring structure for taper tool is not prominent, where as a clear layered, stacked onion ring formation can be observed for taper threaded tool. Comparatively improved tensile properties are achieved for taper threaded tool at higher tilt angles. EDS analysis reveal the presence of higher amount of iron percentage at nugget for welded specimens those experienced higher X force fluctuation and exhibit brittle failure under tensile loading.

1. Introduction

Friction stir welding (FSW) is a solid state joining process which is accomplished by generation of heat at the joining line largely supported by friction between the non-consumable rotating tool and workpiece interface, plastic deformation of the workpiece [1,2]. The final weld quality depends on complex combination of several aspects such as process parameters (tool rotational speed, tool travel speed, tilt angle, plunge rate, vertical force, tool design etc.), material properties (yield stress, shear stress, hardness, thermal conductivity etc.) and weldment cooling strategy (backing plate). Since in FSW material to be joined has to stir to achieve proper plastic deformation, torque generated at tool-workpiece interface has an important role. Different forces also generate at the tool workpiece interface (Fig. 1). The tool in FSW experienced a vertical force (Z force) as it plunges down into the workpiece and as it traverses along the joint line a longitudinal force act on the tool pin known as welding force (X force) due to the material's resistance to flow around the tool pin. Adequate vertical force is an important requirement since it promotes heat generation and proper consolidation of plasticized material at the trailing edge of the tool. Tool design is one of the important parameters that influence the final weld characteristics by influencing the heat generation, degree of deformation of plasticized material and mixing of material between two plates to be welded [3,4].

Elangovan et al. [5,6] extensively studied the effects of different tool design on a range of Aluminium alloy and dissimilar material joining. Their study in almost all cases concluded in favor of flat faced pin tool (square pin tool) due to its capability to produce finer grain by pulsating stirring action. Researchers have shown their interest to study the effects of threaded tool for better mixing of deformed material. Zhao et al. [7] in their study found that screw threaded taper tool produce good bonding quality and mechanical properties by maintaining uniformity in precipitate distribution and finer grain size at nugget. Most of the studies in FSW focused on the effect of tool traverse speed and rotational speed by fixing a constant tool tilt angle which is mostly decided by trial and error method. Comparatively very few literatures are available on the effect of tool tilt angle for different tool geometries. Tool tilt angle has an advantage of complex and intense stirring action in

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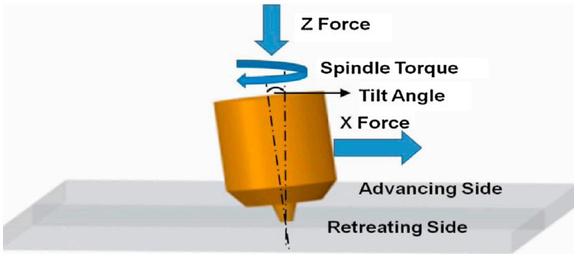


Fig. 1. Schematic representation of spindle torque and different forces for FSW process.

Table 1
Chemical composition and mechanical properties of base plate.

Material	Chemical composition (wt%)						
AA6061-T6	Mg	Mn	Cu	Cr	Si	Fe	Al
	1.2	0.15	0.2	0.04	0.6	0.75	Bal.

Mechanical properties			
YS/MPa	UTS/Mpa	Elongation In percentage	Hardness($HV_{0.1}$)
310	276	18%	107

nugget zone [2]. Chen et al. in their investigation found that tool tilt angle has an influence on heat generation and if properly used defect free welds can be produced [8]. Z.barlas et al. experimentally observed that 2° tilt can produce defect free weld subjected to some other conditions [9]. In this study an effort is given to understand the effect of tool tilt angle on different forces and torque generation for different tool since amount of force and torque and their distribution pattern can explain material status, flow stress etc. In the present study two types of tools extensively used in industries viz. simple taper pin tool and taper threaded tool are considered. The taper threaded tool is a variant of taper tool with threads at the outer circumference of the tool pin. Comparative studies of the results obtained by application of both the tools provide an understanding on the behavior of different parameters involved in the FSW process such as torque, Z force, X force etc. with variation in tool geometry as well as tool tilt angles.

2. Experimental procedures

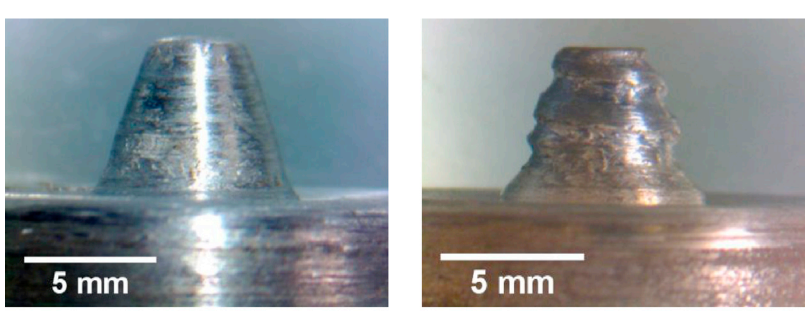
The experiments are conducted in 3-Ton FSW set up on AA6061-T6 plates (120 mm × 130 mm × 6 mm) in square butt configuration. The chemical composition and mechanical properties are stated in Table 1. Tools used in this study are fabricated from high H13 steel. The shoulder diameter of the fabricated tool is 18 mm and top and bottom pin diameters are 6 mm and 3 mm respectively. Both taper and taper threaded tools are used for the study (Fig. 2). Tool tilt angles used in this study are 0° 1.5°, 3° and tool traverse speed, rotational speed is kept constant (1.25 mm/sec, 900 RPM). Most of the literature reported to obtain defect free welds with a tilt angle below 3° whereas use of 0° tilt is also reported to result in defected joints. However 0° tilt is incorporated in the study to analyze how torque and force distribution differentiate with and without tilt angle and their effect on weld zone formation (interms of defect and defect free weld formation) and mechanical properties. To obtain a visually defect free welding for all tilt angles speed and rpm has set iteratively. Dwell time is 4 s and a plunging rate of 20 mm/second is considered with a plunging depth of 0.1 mm. For measurement of spindle torque, Z force and X-force strain gauge based load cell is used which is controlled through a PLC system integrated with IPC and NI LabView software for data acquisition, storage and retrieval. Light optical micrograph is employed for grain size measurement at nugget. Field emission scanning electron microscopy equipped with energy dispersive spectroscopy (EDS) is used to analyze the developments of second phase particles in nugget zone. Tensile test specimens are cut along the transverse direction of welding and prepared according to ASTM E8 standard. Tensile tests of the specimens are carried out at 1 mm min^{-1} strain rate in INSTRON 8801 machine. Fracture surfaces are subjected to scanning electron microscopy (SEM) for fractographic analysis. Hardness profiles are evaluated along the transverse direction of welding by using microhardenss tester at a force of 100 gf and 10 s dwell time.

3. Results

Fig. 3 represents the variation of spindle torque, downward vertical force (Z force) and force applied on tool pin (X force) distribution with respect to time. Fig. 4 represents the variation of their average values with change in tool tilt angle. Average values of torque and force are considered after tool dwelling finishes and tool start to traverse. The initial portion of the transition period where torque and forces are not stable is also incorporated into the average values since difference is not very significant and overall trend of average values for all the welding are same.

Fig. 5 represents the macrostructure of weld cross section for both the tool. It is observed that nugget zone for taper tool don't exhibit any distinct onion ring structure (except 0° tilt) where as onion ring structures are more prominent for taper threaded tool. A small onion ring formation can be observed for taper tool at 0° tilt. For taper threaded tool stacked layers of onion ring has formed due to thread incorporated flow. The onion ring for taper threaded tool is generally shows a split pattern (incomplete half elliptical bended patterns stacked into several layers). For taper threaded tool with 0° and 1.5° tilt only bottom half of the onion ring is prominent in weld zone. But for 3° tilt both half of the onion ring can be observed in nugget zone.

The grain size with their respective ASTM grain number for each welding is stated respectively in Fig. 6. Average grain diameter



(a) (b)

Fig. 2. Tool used during experiment (a) Taper tool (TT) and (b) Taper Threaded tool (TTH).