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EFFECT OF TOOL TILT ANGLE ON MICROSTRUCTURAL CHARACTERISTICS OF FRICTION STIR WELDED LAP JOINTS OF AA2014-T6 ALUMINUM ALLOY JOINTS

***Rajendran C[1], Srinivasan K[2], Balasubramanian V[3], Balaji H[4] and Selvaraj P[5]**

[1]Assistant Professor, Department of mechanical Engineering, Sri Krishna College of Engineering and Technology, Coimbatore.
[2]Assistant Professor, [3]Professor, Centre for Materials Joining and Research, Department of Manufacturing Engineering, Annamalai University, Annamalainagar-608002,
[4]Scientist-D and [5]Group Director, Aeronautical Development Agency, Bangalore.

ABSTRACT

The high strength aluminum alloys such as 2xxx and 7xxx series are suitable for parts and structure requiring high strength to weight ratio and are commonly used in aircraft fuselage and wing skins. The structures are conventionally joined by rivets. It is difficult to join these aluminum alloys especially 2xxx series by fusion welding processes due to break up of oxide layer which usually result in solidification cracking, burn through and porosity. Hence to overcome such problems solid state welding technique is chosen. Friction stir welding (FSW) is one such promising process, which can be effectively applied to weld these alloys for aircraft application with lap joint configuration. In this present investigation, the aluminum alloys 2014 were lap welded by friction stir welding technology. Effect of tool tilt angle on tensile shear fracture load (TSFL) and microstructure properties were studied experimentally. In this present study, the tool tilt angle was varied from 0° to 4° with an interval of 1° while other parameters such as tool rotational speed, welding speed, tool shoulder diameter were kept constant. Tensile shear fracture load, macro and microstructure analysis were performed to evaluate the joint strength. This investigation revealed that defect free friction stir lap welding (FSLW) was achieved by while using tool tilt angle of 1°, 2 °and 3°. However, maximum TSFL of 14.42 kN was exhibited by the joint fabricated using a tool tilt angle of 3° and the results are discussed in detail.

Keywords: *Aluminum alloy, Friction stir lap welding, Tool tilt angle, tensile properties*.

1.Introduction

Friction Stir Welding (FSW) is a solid state welding process developed and patented by The Welding Institute (TWI), UK in 1991 [1], emerged as a new welding technique to be used to join high strength aluminum alloys such as 2xxx and 7xxx series that are very difficult to join by conventional fusion welding techniques. The process was initially developed for Aluminum alloys but now FSW was suitable for joining large number of other metals [2]. Conventional fusion welding of aluminum alloys often produce a weld which suffers from defects, such as porosity, distortion developed as a consequence of entrapped gas not being able to escape from the weld pool during solidification process. In contrast, with SW the interaction of non-consumable rotating tool traversing along the weld line creates a welding joint through plastic deformation and consequent heat dissipation resulting temperatures below the melting point of the materials being joined. Other interesting benefits of FSW compared to fusion welding processes are low distortion, excellent mechanical properties in the weld zone, execution without a shielding gas and suitability to weld all aluminum alloys [3].

FSW can be used to produce Lap, Butt, Corner, T, Spot, Fillet and Hem joints, as well as to weld hollow objects, such as tanks and tubes/pipes, stock with different thicknesses, tapered sections and parts with 3dimensional contours [2 & 4]. The replacement of fastened joints with FSW joints can lead to significant weight and cost savings, attractive propositions for many industries [5]. The basic principle of friction stir welding process is

**Corresponding Author - E- mail: crdrn12@yahoo.com*

remarkably simple. A rotating tool with pin and shoulder is inserted in the material to be joined and traversed along the joint line. The heating is localized and generated by friction between the rotating tool and work piece, with additional adiabatic heating from metal deformation [6-7]. The pin and shoulder of the tool can be modified in number of ways to influence material flow and micro structural formation. Mishra and Ma et.al reported that the recent development of scrolled tool shoulder allows FSW with no tool tilt [8]. Chen et.al. investigated that under the same welding parameters, channel-like defects were observed in the welds produced in tool tilt angle below 1.5° and above 4.5° [9]. They also stated that the tool tilt angle has an essential influence on the heat input and the position of the defects in the weld. Kato et.al. Observed defects in the weld when the tool tilt angle is 0° and above 3° [10]. Barlas et.al. experimentally studied and reported that defect free welds obtained with a tool tilt angle 2°. [11]. Moneer et.al [12]. reported that optimum results were achieved with a tool tilt angle of 2° and tool offset 1mm.

In this study, the AA2014-T6 aluminum alloy was used to friction stir lap weld at different tool tilt angle of 0^o,1^o,2^o,3^o, and 4^o under constant welding process parameters. The aim of this work is to understand the influences of the tool tilt angle on the microstructure and lap shear strength.

2. Experimental

AA2014-T6 aluminum alloy sheet 3 mm thick was used as test coupon material for friction stir lap welding (FSLW). Chemical composition and mechanical properties of base material are shown in Table 1-2. The tool used for this investigation was M2 grade (heat treated and 62 HRC hardened). The dimension of FSW tool used presented in Table 3.

Table 1. Chemical composition (wt. %) of base metal

Si	Fe	Cu	Mn	Mg	Zn	Cr	Ti	Al
0.8	0.13	4.8	0.8	0.7	0.06	0.05	0.01	92.4

Table 2. Mechanical properties of base metal

Material	0.2% Yield stress (MPa)	Ultimat e tensile stress (MPa)	Elongation in 50 mm gauge length(%)	Micro hardness 0.5N, 15 sec (HV)
AA2014	431	463	10	163

An indigenously developed CNC controlled FSW machine was used for this investigation. Experiments were carried out for five different tool tilt angles 00, 10, 20, 30, and 4O wherein other parameters such as tool rotational speed, tool traverse speed, tool shoulder and pin diameter, and axial load were kept constant (Table 4). After, the weld was carried out, the samples were first checked visually (from front to back) and then subjected to macrostructure examination, tensile shear fracture load test and micro hardness test were evaluated.

Table 3. Nomenclature of the FSW tool

Pin description	Pin diameter		Pin length (mm)	Taper angle in pin (°)	Thread pitch (mm)
	Major diameter (mm)	Minor diameter (mm)			
Threaded taper pin	2.0	1.5	1.5	9.46	0.75

Table 4. FSLW process parameters and its value

Sl. No	Process parameters	Values
1	Tool rotational speed	900 rpm
2	Welding speed	90 mm/min
3	Tool shoulder diameter	18 mm
4	Tool pin diameter	6 mm
5	Tool tilt angle	0^o,1^o,2^o, and 3^o
6	Pin type	Left hand threaded tapper cylindrical pin
7	Shoulder concavity	1^o

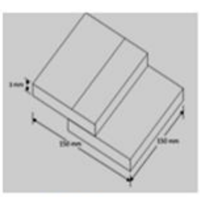
All the metallography specimens were prepared by mechanical grinding, polishing (1000,1500,2000, and 2500 grade emery paper) followed by alumina powder. The specimen was etched by Keller's reagent and swabbed on the cross - section of the weld for microstructure analysis. Transverse lap shear specimen were prepared as per the ASME/AWS/SAE/D8.9-97, three specimens were tested for each condition to check the repeatability. The micro hardness was measured after every 0.5 mm indentation at 0.5 N load and 15s dwell time along the transverse cross section of the welded specimen. The joint efficiency of FSLW specimen under lap shear loading was estimated using the following formula, which was proposed by Cederqvist and Reynolds [21],

$$\text{Joint efficiency} = \frac{\text{Weld failure load}}{\text{Base material failure load}} \times 100 \qquad (1)$$

3. Result & discussion

3.1. Macrostructure

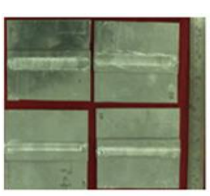
Table 5 shows the weld surface appearance and cross-section of the weld produced using different tool tilt angle (0^o to 4^o). The top surface of the weld appeared clean and no obvious defects could have identified, in which welded with tool tilt angle of 1^o to 3^o. The ripples observed on the surface of the welds may be attributed to mechanical shanking effect caused by the variation in the stress state of the deformed metal during change in tool tilt angle. There was some surface defect on the FSLW joint fabricated in low and high tilt angle. The mechanism behind the FSW process is friction between the tool and the base metal generates heat, which with rotation of the tool causes severe plastic deformation of material.



(a)

(b)

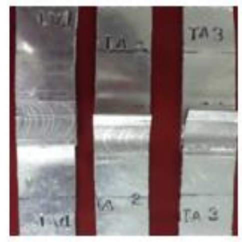
Fig.1a . A schematic diagram of FSLW and Fig. 1b. Photograph of fabricated FSW tool



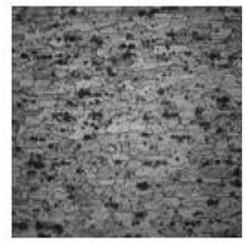
(c)

(d)

Fig.1c. Photograph of FSLW joints and Fig. 1d. Photograph of tensile specimens (Before testing)



(e)



(f)

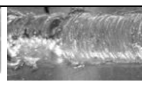
Fig.1e. Photograph of tensile specimens and Fig.1f. Optical micrograph of BM (after testing)

The weld is created through forging of the deformed material into the cavity that develops behind the tool from the Retreating Side (RS) to the Advancing Side (AS). The gap between the tool and the work piece made from the tilt of the tool expands by increasing the tilt angle. Therefore, by increasing the tilt angle, the plasticized material escapes easily from the bottom of the tool shoulder. Consequently, a discontinuity occurs in the weld, which leads to the formation of some voids at the surface. As can be seen (Table 5) in tilt angle 4^o lack of material in RS and the increasing the tilt angle facilitates removal of the material away from the bottom of the tool. On the other hand, with decreasing tilt angle, forging of the material will not take place; thus the weld will not develop.

Whereas, the defect free joints were noticed from 1^o to 3^o, eventually the stir zone shape and size was changed with increase in tool tilt angle. The incomplete or lack of fill defect was observed on the surface of weld made at 0^o tool tilt angle, due to insufficient material flow around the pin.

Additionally, the tool tilt angle increases from 1^o to 3^o with an increment of 1^o, the increase in tool tilt angle resulted increase in heat generation and high forging force [13, 14]. The forging force was increased as the tool tilt angle increases and the second one, when the pin is threaded can also accelerated more volume of plasticized material and pushes the material in downward direction [15]. However, the weld made at 4^o tool tilt angle causes thinning effect on the localized weld region. Hence, effective sheet thickness was reduced resulted poor weld strength, because the gap between the tool and the work piece made from the tilt of the tool expands by increasing the tilt angle.

Table 5 Macrograph and weld surface

SlNo	Tilt angle	Macrograph	Weld surface	Probable reason
1	0			Lack of fill defect-Insufficient material flow.
2	1			Insufficient consolidation
3	2			Sufficient forging force due to increase in tool tilt angle
4	3			High forging force resulted good consolidation and good material mixing
5	4			Lack of fill defect -Material escape due to high tilt angle.

Therefore, by increasing the tilt angle, the plasticized material escapes easily from the bottom of the tool shoulder [16]. Consequently, a discontinuity occurs in the weld, which leads to the formation of some voids at the surface (Table 5). Therefore, there is an optimum tool tilt angle in FSLW; which was found to be 3^o for AA2014-T6 aluminum alloy. Another one important criteria in FSW process in aluminum alloy weld is onion ring formation. The significance of onion ring formation is material flow around the pin, in which it indicates the flow of plasticized material in the stir zone in uniform pattern [17]. In the weld made with 1^o tool tilt angle generated a number of concentric onion rings (Fig 2a). Even though, two no of onion ring region was formed over to another when welded with 2^o tool tilt angle (Fig 2b), likewise, when the FSLW made using 3^o tilt angle produced three no of onion ring region one over by another one (Fig.2c). It could be indicative that the flow of material in downward and upward in the stir zone.

3.2 Microstructure

The cross section can be divided into four microstructural zones, i.e., base metal (BM), heat affected zone (HAZ), thermo-mechanically affected zone (TMAZ), and stir zone (SZ). Typical microstructures in different locations of a FSLW at different tool tilt angle of 1^o, 2^o and 3^o are shown in Fig.2. In the BM, the grains are elongated along the rolling direction (Fig. 1f). The HAZ only experiences the welding thermal cycle, and the grain size in this zone is similar to that in the BM. The TMAZ on AS and RS undergoes both the welding thermal cycle and the shear stress during the FSLW. The grains in this zone are strongly distorted, and partial dynamic recrystallization occurs (Fig. 2-5).

The SZ is stirred directly by the welding tool, and the fine and equiaxed grains can be obtained (see Fig. 2-5). This implies that complete dynamic recrystallization occurs in this zone [18, 19]. From the Fig.2, It can observe that the weld made with tool tilt angle 3^o exhibited finer grain (Fig.2c) than other FSLW joints and subjected to severe material processing take place by the high forging force. where as in TMAZ on AS has much variation in the weld made with 3^o tool tilt angle compared with other joints due to more tilt angle caused high heat input and good consolidation, moreover a clear boundary is visible in between TMAZ and WNZ on AS, which is not observed in the retreating side.

3.3 Lap Shear Strength and Fracture Location

Tensile strength of FSLW joint are presented in Table 6. The maximum lap shear strength of 14.42 kN exhibited, when welded with 3^o tool tilt angle [22]. The other joints have lower lap shear strength due to the redistributed Alclad which penetrates into the SZ, which may be a preferred crack propagation path during tensile shear testing, because it is much softer than aluminum alloy. Therefore, the morphology of the redistributed Alclad in the SZ has significant influences on the tensile shear property of the FSLW joint. The higher tool tilt angle makes the redistributed Alclad in the SZ more disperse, and this prevents the redistributed Alclad from being a preferred crack propagation path in the tensile shear test.

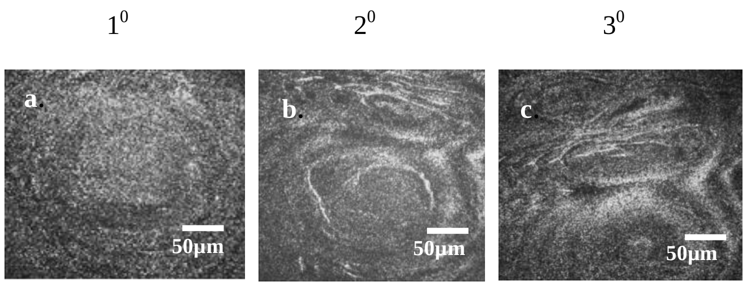


Fig.2 Micrograph of stir zone

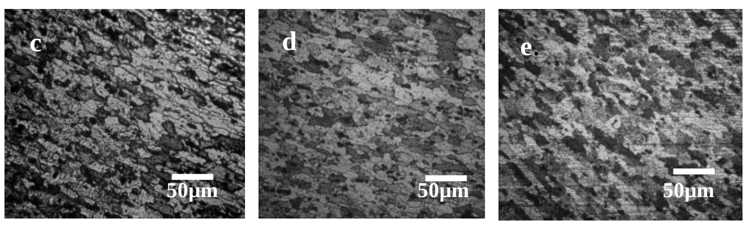


Fig.3 Micrograph of TMAZ-AS

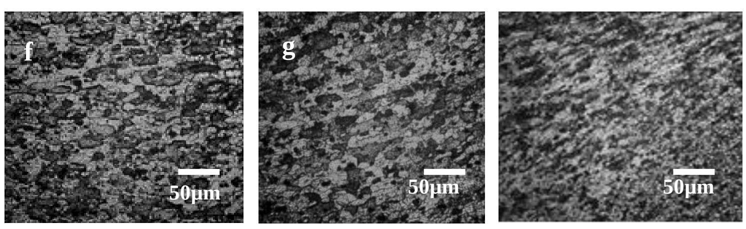


Fig.4 Micrograph of TMAZ- RS

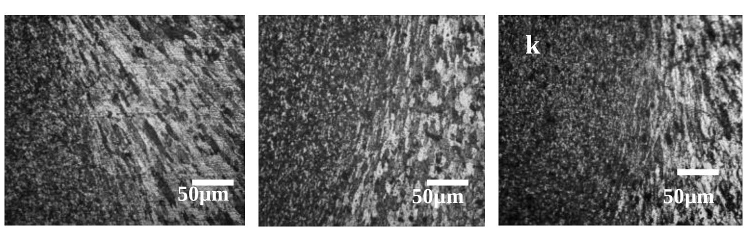


Fig.5 Micrograph of interface (TMAZ/SZ)

Table 6 Mechanical properties of FSLW joints

Sl. No	Tool tilt angle	Micro hardness 0.5kg,15 sec	Tensile shear fracture load (TSFL) kN	Area of stir zone mm^2	Joint efficiency (%)
1	1^0	118	12.60	16.00	74
2	2^0	125	13.10	16.72	77
3	3^0	136	14.42	16.80	84

The 90% of fracture location in FSW always at the interface between TMAZ and SZ on advancing side; this is due to thermal softening and grain coarsening during thermal cycle. In the weld made with 1^o and 2^o tilt angle the fractured occur on the SZ due to in sufficient consolidation, because lower tilt angle produces less heat generation and lower forging force, this is the reason for the fracture occurred in the SZ.

The fracture location of FSLW made with 3^o tool tilt angle was on the AS on the top sheet and RS on the lower sheet, because the lower sheet on the retreating side is most vulnerable to failure than the advancing side of the upper sheet [20]. The maximum hardness of 135 HV was achieved, when the weld made with the tilt angle of 3^o.

4. Conclusions

From this investigation, the following important conclusions are drawn

- Of the five FSLW joints fabricated by maintaining 3^0 tilt angle registered a maximum tensile shear fracture load of 14.42 kN and showed a joint efficiency of 84%.
- At lower tool tilt angle, the FSLW joints exhibited low strength due to the insufficient flow of material and low forging force in the stir zone.
- At higher tool tilt angle caused excess flow of material in the stir zone resulted in low strength.
- Formation of closely spaced onion rings, formation of finer grains in stir zone and higher hardness of stir zone (135 HV) are the reason of superior performance of the joint fabricated by maintaining 3^0 tool tilt angle than other joints.

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