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Experimental Study on Temperature Evolution during Friction Stir Welding of 2014-T6 Aluminum alloy, Structure-Property Correlation

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Abstract:- This study aims to measure the temperature at a location very near to the stir zone during friction stir welding of 6mm thickness 2014-T6 Aluminum alloy under different process parameters like weld speed, tool pin profile of varying concave shoulder radius of R3 & R3.5 at constant tool rotational speed. Thermo couple of K-type is inserted in the pre-grooved hole of 2.5mm diameter on the advancing side of the work piece at a distance of 6mm from the centre line of the two plates to be joined. The location is selected such that, it is at exactly half the length of the work piece. The welded joints were made such that they are free of internal defects. Temperature was measured using the thermo couple during FSW at specified location on the work piece in the welding direction. To study the effect of tool pin profile, temperature measurements were made in the region adjacent to the rotating pin, close to the nugget in the thermo mechanical affected zone (TMAZ). Experimental results shows that by increasing the tool rotation speed, temperature rises to a maximum using concave shoulder radius of R2.5 mm, due to larger contact area increasing the heat input required for sufficient plasticized deformation thus improving the mechanical properties. It is observed that during FSW extensive deformation is experienced at the nugget zone and the evolved microstructure strongly influences the mechanical properties of the joints.
The present study also aims at understanding the influence of pin profile on the micro structural changes and the associated mechanical properties.
Keywords: Friction Stir Welding, microstructure, temperature, mechanical properties

1. Introduction

Friction Stir Welding (FSW) is an important solid state joining process invented at The Welding Institute(TWI) of UK in 1991[1] by Wayne Thomas as it makes high quality welds for number of materials as compared to the conventional welding techniques. In FSW process, a non-consumable welding tool is used to generate the frictional heat between the tool and the work piece. Due to this frictional heat, the surrounding material softens and allows the tool to be involved along the joint line [2]. The material is plasticized and translated along the welding direction and is transported from the leading edge of the tool to the trailing side. Subsequently, it produces a high quality joint between the two plates by the translation movement of the work piece along with the applied pressure of the tool [3]. FSW is environment friendly , energy efficient, less distortion and faster welding speeds than conventional fusion welding techniques and be able to join materials that are difficult to fusion weld [4]. Welding is done due to the heat generation between the tool and the base plates. The weld quality depends on various process parameters like weld speed, tool rotation speed, tool pin profile, tool tilt angle, axial force and joining materials. Tool rotation speed is one of the main factors affecting the frictional heat. When the welding speed is small, the frictional heat makes the temperature in the weld to increase considerably. On the other hand when the welding speed is large, the frictional heat is not enough to plasticize the materials. For fabricating defect free FSW joints, heat generation is one of the major factors. Studies were made on the thermal distribution during the FSW process at different process parameters and their modeling strategies are studied through the thermal distribution in the base material [5]. Janaki Ramulu et.al [6] investigated the temperature evolution during friction stir welding of 6061-T6 Aluminum alloy and found that by increase in shoulder diameter, plunge depth and tool rotation speed the peak temperature is increased, whereas for increase in weld speed it decreased. The present work aims at monitoring the temperature evolution in a friction stir welded joint of 2014T-6 AA under different process parameters like varying weld speed, different radius of concave shoulder, constant tool rotational speed and constant plunge depth and correlate with the mechanical and micro structural properties.

2. Experimental Procedure

The experimental study includes the butt joining of 6 mm 2014T-6 Aluminum alloy. The welding process is carried out on a vertical milling machine (Make HMT FM-2, 10hp, 3000rpm).Tool is hold in tool arbor and special welding jigs and fixtures are designed to hold two plates of 200 mm X 60 mm X 6 mm thickness as shown in Fig.1. FSW process parameters and tool specifications are mentioned in Table 1. These combinations are chosen based on the literature survey and the capability of the milling machine used for the

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experimental study. Mechanical properties of the base metal are presented in Table 2.

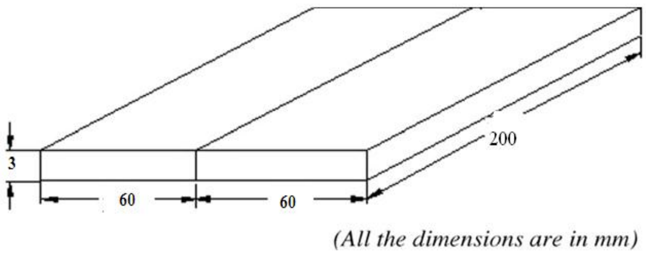

Fig.1. Schematic sketch of the weld joint

Table 1: FSW process parameters and tool specifications

Process Parameters	Values
Tool rotation speed (rpm)	1800
Welding speed (mm/min)	16,20,31.5,40
Axial force	Constant
Pin length (mm)	5.6
Tool shoulder diameter, D (mm)	24
Pin diameter, d (mm)	8
D/d ratio of tool (mm)	3
Tool pin geometry	Straight cylindrical pin profile with varying concave shoulder radius
Tool material	H-13 tool steel

Non consumable tool made of H-13 tool steel is used to fabricate the joints because of its high strength at elevated temperature, thermal fatigue resistance and low wear resistance and diameter of shoulder is 24 mm and pin used were 8mm and the length of the pin is 5.6 mm. The tools used for the present study are straight cylindrical pin profile with varying concave shoulder radius of R3 and R3.5 as shown in Fig. 2. A constant axial force is applied for the entire FSW experiments. K type thermo couple is used to measure the temperature at the specified location. The joints were found to be defect free from their surface morphology as shown in Fig.3.

Table 2: Mechanical properties of base metal

B.M	UTS (MPa)	YS (MPa)	% El	Micro Hardness (HR_v)	Impact strength (J)	Melting point(^{0}C)
AA 2014T-6	483	414	13	155	6	507-638

Fig.2. Tools with varying concave shoulder radius (a) R3, (b) R3.5

Fig.3. Surface morphology of weld

2.1 Temperature measurement

The pre-grooved hole of 2.5mm is made using a conventional vertical milling machine (wheel cutter) at a distance of 6mm from the centre line of the abutting surfaces. The specified location for the insertion of thermo couple is taken at a distance of 100mm form the leading edge of the plates. Fig.4. shows the set up with the insertion of thermo couple into the base metal.

Fig.4. Set up showing the k-type thermocouple inserted into the base plate.

The thermo couple is connected to a digital indicator which records the temperature at the specified location which is 6mm away from the pin for all the experiments. The temperature is recorded in the shoulder influenced region.

2.2 Metallography

The specimens for metallographic examination were sectioned to the required dimensions from the FSW joints in transverse to the welding direction, polished with different grades of paper, and then etched with Keller's reagent. The microstructure of the stir zone (SZ) and the unaffected BM were examined with optical microscopy (Model; Nikon; Make: Epiphot 200), and changes in the microstructure of the SZ were found.

2.3 Mechanical Testing

Tensile specimens were machined as per ASTM E8M in the transverse direction from the welded joints. Tensile test was carried out in 60 tons, servo controlled Universal Testing Machine (Make: FIE-Blue star, India; Model: TUE-600©).The specimens were loaded at the rate of 1.5kN/min as per ASTM specifications. Specimen for impact test is taken in transverse to the weld direction and machined as per ASTM A370 standards. The Charpy V notch impact test is conducted at room temperature.

3. Results and discussions

3.1 Microstructural Studies

FSW is a severe plastic deformation process. The stirring action was observed at the weld centre and produces finer grains. This can be clearly reflected in the observed microstructures of the SZ produced by using concave shoulder of varying radius of a straight cylindrical tool pin profile as shown in Fig.4 (a-h).

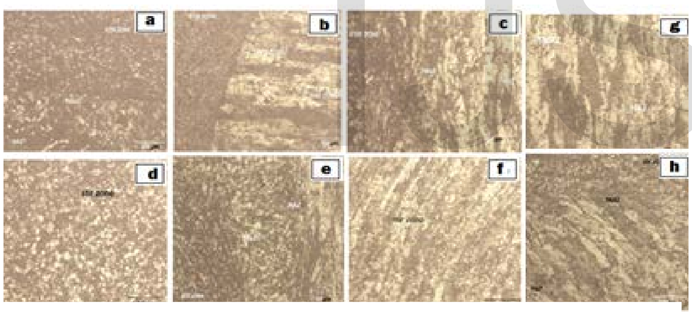

Fig.4. Microstructural images obtained at various conditions Expt's No a-h as given in Table 3.

It is observed that, the joints obtained at 1800rpm, 16mm/min & concave shoulder radius of R3 (Fig. a) resulted in smaller and finer grains compared to other conditions due to sufficient heat generation as the temperature recorded is maximum (4630c). The stirring action of tool induces high amount of plastic deformation and frictional heat generation between the tool and base metal. This is due to the mechanism of constant dynamic recrystallization (DRX). The DRX usually occurs in stir zone and thus the microstructure is refined [7].Small portions of TMAZ and HAZ are observed in between SZ and BM. The TMAZ consists of a slightly elongated grain structure due to the annealing effect of heat and severe plastic deformation of material around the pin edge. DRX is of great interest due to the new grains being smaller than the initial grains which improves mechanical properties. In order to obtain the required amount of heat for defect free welds and better mechanical properties, a novel approach in the design of tool was thought of by reducing the contact area between the shoulder and BM plates by incorporating concave shoulder radius. The tool with concave shoulder radius R3 had larger contact area when compared to other tool of radius R3.5 yielding the required heat and better flow of material for obtaining better mechanical properties which can be clearly observed in the microstructure.

3.2 Mechanical Properties

Mechanical properties of the joints fabricated at constant tool rotational speed (1800rpm) and different welding speeds (16, 20, 31.5, 40mm/min) using straight cylindrical pin profile with varying concave shoulder radius are given in Table 3. From the results it was found that the joint fabricated with 1800/16/R3 condition (Expt.No a) exhibited superior tensile properties compared to other joints which is attributed to the formation of finer grains due to DRX and maximum heat generation due to higher temperature recorded. Impact toughness of the joints was evaluated. The joint made at the optimum condition resulted higher value compared with other joints.

Table 3: Mechanical properties of joints at various conditions and the temperature values recorded at constant tool rotation speed (1800 rpm); C.S-Concave Shoulder, TS-Transverse speed, UTS-Ultimate tensile strength, YS-Yield strength, El-Elongation, I.S-Impact Strength, T-Temperature

Expt. No	C.S radius, R(mm)	T.S (mm/min)	UTS (MPa)	YS (MPa)	El (%)	I.S (J)	T (^{o}C)
a	3	16	219.27	177.29	2.81	4	463
b	3.5	16	199.46	156.45	2.1	4	438
c	3	20	183.2	144.9	1.45	2	420
d	3.5	20	143.64	113.73	1.53	4	368
e	3	31.5	156.17	123.66	2.06	4	390
f	3.5	31.5	160.09	126.36	2.04	2	422
g	3	40	172.79	139.79	2.74	2	382
h	3.5	40	199.46	156.45	2.90	4	428

3.3 Temperature Measurements

The temperature is measured with respect to FSW process parameters as listed in Table 3 above. Maximum temperature is recorded for Expt. No (a) at 1800rpm/16mm/min/radius R3 due to higher rotational speed, lower weld speed and larger contact area resulting in sufficient heat generation for obtaining finer grains in the SZ compared to other conditions which can be clearly seen in the mechanical properties and microstructural images. Fig.5.

shows the temperature recorded for various Experimental conditions a-h.

CONCLUSIONS

From the present study, the following conclusions were drawn.

- All the process parameters selected have a significant effect on the temperature evolution during FSW
- The tool pin profile with radius of curvature R3 on the shoulder produced more frictional heat than R3.5 due to large contact area of the shoulder with the base metal .
- By increasing the tool rotation speed, the peak temperature is increased, whereas it is decreasing for increasing welding speed.
- Refinement of grains and improved mechanical properties are obtained for optimum condition due to temperature rise ensuring adequate plasticity of the material

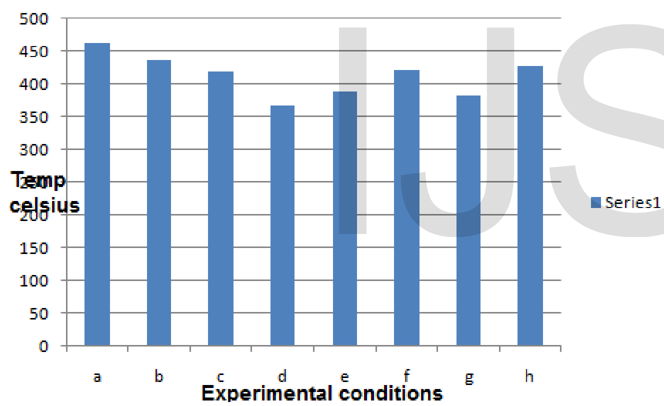

Fig.5. showing the temperature values for various experimental conditions in degree Celsius

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