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Effect of Tool Design and Process Variables on Mechanical Properties and Microstructure of AA6101-T6 Alloy Welded by Friction Stir Welding

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ABSTRACT: *Friction stir welding (FSW) has a potential for wide-spread applications. However, it is necessary to overcome some challenges for its wide-spread usage. Tool design and selection of process variables are critical issues in the usage of this process. This paper tackles the same issues for AA6101-T6 alloy (material used for bus bar conductor, requiring minimum loss of electrical conductivity and good mechanical properties). Two different tool pin geometries (square and hexagonal) and three different process variables, i.e. rotational speeds and welding speeds were selected for the experimental investigation. The welded samples were tested for mechanical properties as well as microstructure. It was observed that square pin profile gave better weld quality than the other profile. Besides, the electrical conductivity of the material was maintained up to 95% of the base metal after welding.*

Keyword: *FSW, Microstructure analysis, Mechanical properties, Electrical conductivity*

I. INTRODUCTION

Friction Stir Welding (FSW) technique was developed before two decades by 'The Welding Institute' (TWI), UK as a novel solid state joining process for Al alloys. Later, it has been developed and used for many other metals, composites and high melting alloys. Friction stir welding (Fig. 1) is a solid state joining process using a rotating tool moving along the joint interface, generating heat and resulting in a re-circulating plasticized material flow near the tool surface[1-3]. This plasticized material is subjected to extrusion by the tool probe rotational and linear movements leading to the formation of stir zone. This stir zone formation is affected by the material flow behavior under the action of rotating tool.

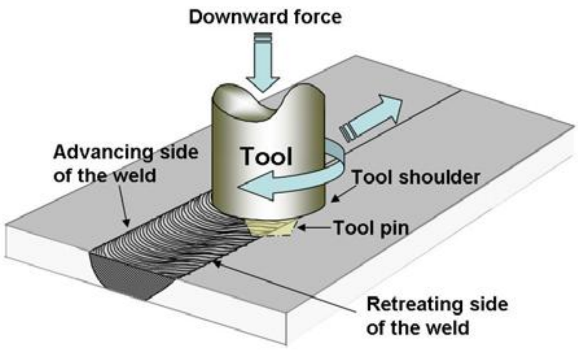

Fig. 1: Basics of Friction Stir Welding

The FSW process is applicable presently for welding of aluminium and magnesium alloys as well as other non-ferrous and ferrous materials like copper, steel, composites and dissimilar materials[4-5]. Welding of heat treatable AA6xxx Al alloy by FSW [6] gives better quality weld compared to other fusion welding process. Elangovan et al.[7] reported the effect of process parameters on mechanical properties of FS welded AA6061 aluminium alloy. They found that the tensile strength initially increased with an increase in tool rotational speed, welding speed and axial force. But the tensile strength decreased with further increase in these parameters after reaching a maximum value. They also studied the pin profile and rotational speed effects on stir zone of AA6061 and AA2219 aluminium alloy and investigated that square pin profile gives better results and less defects as compared to cylindrical, conical, threaded cylindrical or triangular profiles. Aluminum & aluminum alloy are difficult to weld, requiring weld pool shielding gas and specialized heat sources, require the oxide layer to be stripped off prior to or during the welding process. In addition, aluminum and its alloys are subjected to voids and solidification cracking defects when they cool from a liquid state. Consequently, in order to manufacture large panels of aluminum and aluminum alloys, extrusion has become choice of manufacturing. However, even extrusion has size limitations. As compared to the conventional welding methods, FSW consumes considerably less energy. No cover gas or flux is used, thereby making the process eco-friendly. The joining does not involve any use of filler metal and therefore any aluminum alloy can be joined without concern for the compatibility of composition, which is an issue in fusion welding. Since no melting occurs during FSW, the process is performed at much lower temperatures than conventional welding techniques and circumvents many of the environmental and safety issues associated with these methods. The current status of FSW research has been summarized by Mishra and Mahoney[9]. It is clear from the report that the microstructure and resulting properties produced during FSW of aluminum alloys are dependent on several factors like alloy composition, alloy temper, welding parameters, thickness of the welded plates as well as the shape and geometry of applied tools. These changes are evident in age-hardenable alloys where severe plastic deformation accompanied by mixing of material as well as heating and cooling cycles alters the microstructure (and thus properties) in a significant manner. The quality of friction stir welding depends on the geometry of tool pin and shoulder. The process parameters also affect the quality of weld i.e. tool rotation speed, traverse speed, tool tilt angle, D/d ratio, where D indicates diameter of shoulder & d indicates diameter of tool pin, etc. In the present paper, the effect of tool design and process parameters on AA6101 T6 aluminium alloy is studied and results are reported for mechanical properties and microstructure.

II. EXPERIMENTAL WORK

The rolled plates of 6 mm thickness AA6101 aluminium alloy were cut into size 100 mm x 100 mm and machined with square butt joint configuration. The initial configuration was obtained by securing the plates in butt position using specially designed and fabricated fixture. The direction of welding was normal to the rolling direction. Welding was carried out in a single pass using non-consumable tools made of EN24 steel and H-13 tool steel. The chemical composition of the AA6101-T6 material used in the present study is given in Table 1. The mechanical properties of AA6101-T6 were obtained from the laboratory testing.

Table 1 Chemical composition of work material AA 6101-T6

Elements	**Percentage**
Al	Balance
Mg	0.6
Si	0.5
Zn	0.021
Cu	0.074
Cr	0.015

An indigenously modified (with digital speed setting) machine with an in-house developed FSW setup was used in the present study. Two different tools, *viz* hexagonal pin with concave shoulder and square pin with flat shoulder were used to fabricate the joints. Based on the literature coupled with availability of speeds on the machine, three different rotational speeds and traversing speeds were selected to carry out the experiment. The welding parameters and tool dimensions are as shown in Table 2.

Table 2: Welding Parameters and Tool Dimensions

Process parameters and tool details	Values
Rotational speed (rpm)	545, 765, 1070
Welding speed (mm/min)	50, 78, 120
D/d ratio of tool	3.0
Tool shoulder diameter, D (mm)	18.0
Pin diameter, d (mm)	6.0
Tool tilt angle (o)	0.0
Shoulder penetration in work surface (mm)	0.2

The welded samples were sliced and machined to the required dimensions to prepare tensile specimens. ASTM standard was followed for preparing the test specimen. The tensile test was carried out as per ASTM E8 standard. Fig. 3 shows the dimensions of the tensile specimen as per ASTM E8 standard.[10]

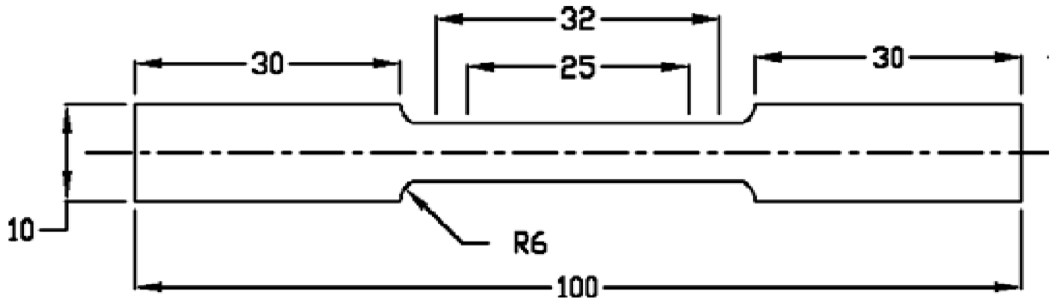

Fig. 3. Tensile test specimen

The face bend test was carried out as per ASME section IX. The bend test was performed on the universal tensile testing machine. The bending diameter of mandrel was 24 mm and bending angle was 1800. After welding the microstructure analysis was carried out with help of Neophot 2 and scanning electron microscope at 250X magnification. 4M Keller's reagent was used as etchant for the development of microstructure. The immersion time for the etching was 1 to 3 min[11]. AA 6101 T6 is the alloy that posses the highest electrical and thermal conductivity among all other Al alloy. The AA 6101 T6 is widely used for making electrical bus bar conductor and butt joint is a mandatory requirement for making it. Therefore, after friction stir welding, it should posses the electrical conductivity nearer to the base metal. The electrical conductivity measurement was carried out using the digital conductivity meter with reference to International Annealed Copper standard (IACS). The hardness of the weld samples was measured in such a way that it covers each and every zone generated at the both side of weld, i.e. advancing and retreating side. The diameter of indenter was 2.5 mm and the load applied was 31.25 kg.

III. RESULTS AND DISCUSSION

From the tensile test result, it was observed that the weld sample prepared at 765 rpm tool rotation speed and 120 mm/min welding speed with hexagonal pin profile possesed the highest ultimate tensile strength i.e. 144 MPa with per cent elongation of 21.88% and fracture occurred at the base metal region indicating pure ductile behavior. In the case of weld prepared by square pin profile with 765 and 1070 rpm at 78 mm/min welding speed, the ultimate tensile strength was found to be 125 and 128 MPA respectively whereas per cent elongation was found to be 25.56% and 20.84% respectively. The fracture occurred at the base metal region at the advancing side of weld indicating pure ductile behavior.

(a)


(b)


Fig 4. Face Bend test specimen welded by (a) hexagonal tool pin tool (b) square pin tool

The bend test result indicated that the weld did not have any kind of opening or crack after the face bend test and it showed satisfactory performance of weldments as per ASME section IX (Fig. 4). The typical microstructure of as received conditions (base material) is shown in Fig. 5; which shows that the microstructure comprises of the coarse grains of aluminum with the hardening precipitates of Mg_2Si.

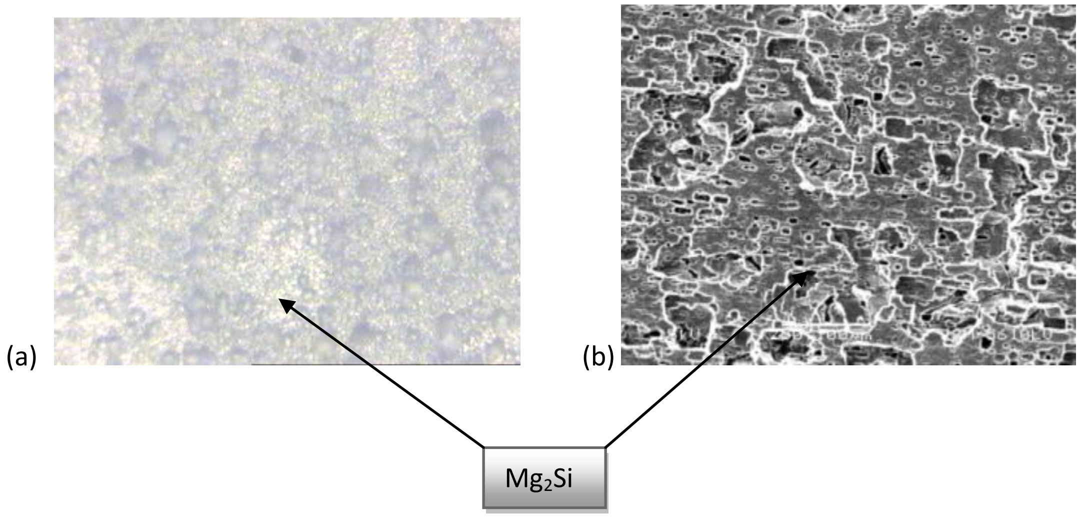

Fig. 5. Showing the microstructure of the AA 6101 T6 Alloy.a.at Neophot, 250x b. at SEM ,250x

Microstructure analysis showed different zones in the weld samples. These zones are: weld centre, nugget zone, thermo mechanically affected zone, heat affected zone and unaffected or base metal region. The reasons for formation of nugget region in the centre of the weld are still unknown and an extensive research is going on to find out the origin of nugget region.

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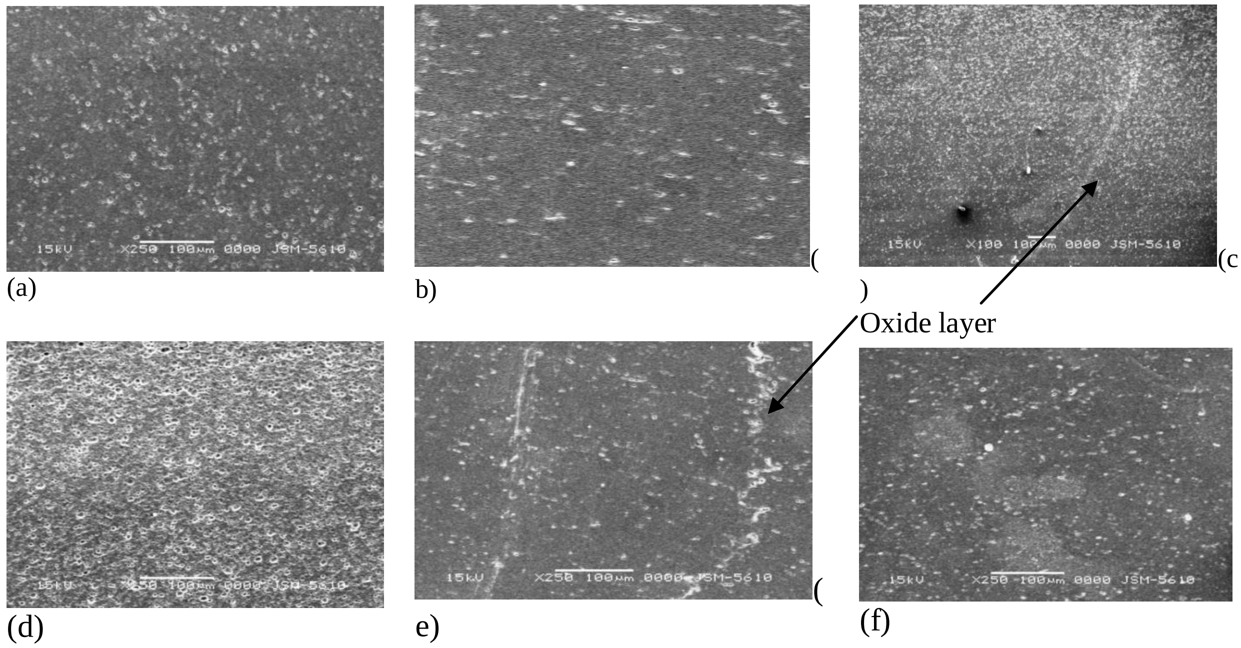
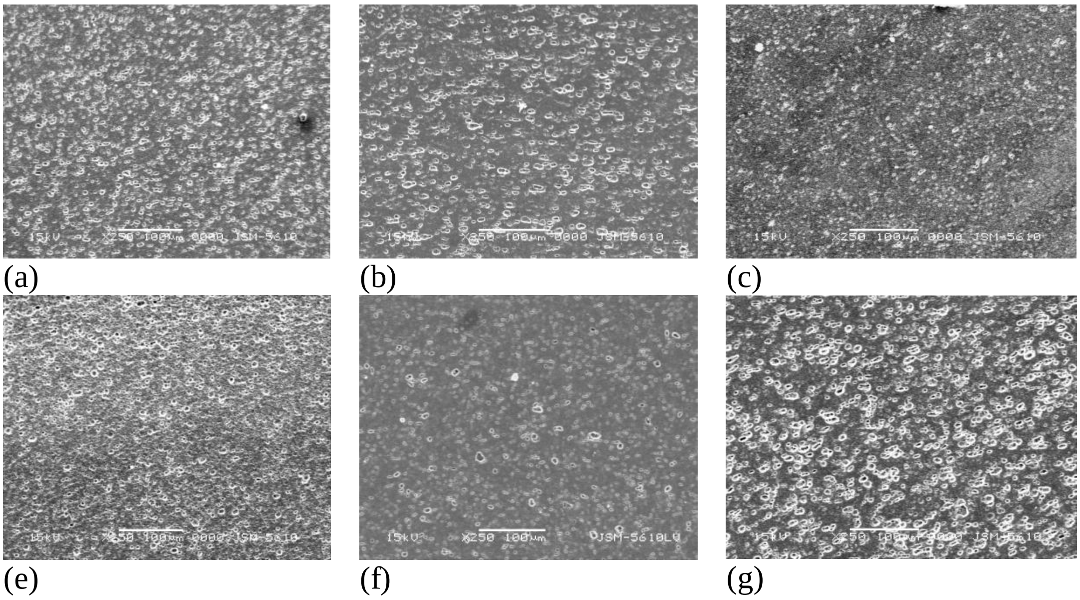


Fig. 6. SEM analysis of sample at 250x, prepared by Hexagonal pin tool: (a) HAZ at AS, (b) TMAZ at AS, (c) weld centre, (d) Nugget, (e) TMAZ at RS, (f) HAZ at RS,

The weld centre consist of extremely fine recrystalized grains of Al with the breaking of the coherent precipitates of Mg_2Si. The size of the precipitates are extremely finer compared to the other zone of the weld. The distribution of the precipitates is uniform throughout the weld centre region. Severe plastic deformation was observed and the precipitates were found to be destroyed and also some re-precipitation was observed. Also, formation of some oxide layer at either at the advancing side or at the retreating side of the weld sample was observed; forming some uneven boundary between the weld centre and the TMAZ and thus making some differentiation between them.



(a) (b) (c)
(e) (f) (g)

Fig. 7. SEM analysis of sample at 250X, prepared by Square pin tool: (a) HAZ at AS, (b) TMAZ at AS, (c) weld centre, (d) Nugget, (e) TMAZ at RS, (f) HAZ at RS.

In the TMAZ, the microstructure consisted of extremely fine grains of the Al with fine size of the precipitates of Mg2Si. There is presence of more precipitate free zones compared to weld centre. There is formation of an oxide layer at boundary near the TMAZ and weld centre, mostly on retreating side of weld done by hexagonal pin. A nugget region was observed near the bottom root portion of the weld centre region. The nugget region comprised of banded structure. It is also called as onion ring structure. The bands are distributed in such a way that there was formation of alternate bands of light and dark bands with different coherency and density difference of precipitates.[12] The HAZ formed on the both the side of the weld, i.e. advancing and retreating side of weld. The reason behind formation of the heat affected zone is temperature difference across the weld. Since the alloy plate was at room temperature before welding. When the welding was done by the rotation of tool, there was substantial increase in temperature due to the friction generated between the tool and work piece and due to the plastic deformation of work piece. Hence, grain growth was observed in the HAZ. The microstructure comprised of the coarse grains of aluminum with ripen precipitates of the Mg2Si.

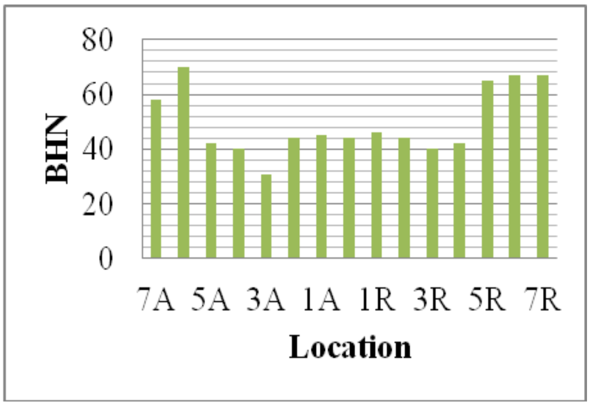


Fig. 8. Hardness profile of weldment

The hardness test indicated that there was an average 57 % reduction in the hardness level in the weld region compared to the base metal (Fig. 8). The electrical conductivity measurement showed negligible decrease in the electrical conductivity after welding; indicating gradual reduction in grain size and proper distribution of the Mg_2Si precipitates.

IV. CONCLUSIONS

In the present study, the effect of process variables and tool design on friction stir welding of AA 6101 T6 Al alloy was studied and based on the results the following conclusions can be drawn:

- The weld prepared by square pin profile possessed better mechanical properties and microstructure compared to the one prepared by hexagonal pin profile.
- During the friction stir welding by hexagonal pin profile, oxide layer was found in most of the cases. Also, a continuous tunnel was found at the bottom side just above the bottom skin of the material.
- Process parameters and tool profile had an effect on the quality of welding.
- During tensile test, fracture occurred at the base metal region at the advancing side of weld; indicating pure ductile behavior proving the welded joint stronger.
- Loss of conductivity after welding was found to be negligible.

V. Acknowledgement

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