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Investigation of mechanical properties of aluminium 6061 alloy friction stir welding

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Abstract
Aluminium 6061 alloy is commonly used for construction of aircraft structures, such aswingsandfuselages, more commonly in homebuilt aircraftthan commercial or military aircraft.Aluminium 6061 alloy generally present low weldability by traditional fusion welding process. The development of Friction Stir Welding (FSW) has provided an alternative improved way of satisfactorily producing weld joint in aluminium 6061 alloy. In FSW, the welding tool motion induces frictional heating and severe plastic deformation and metal joining process is done in solid state results, which results in defect free welds with good mechanical properties in aluminium alloy 6061. Unlike in traditional fusion welding, friction stir welds will not encounter problems like porosity alloy segregation and hot cracking, and welds are produced with good surface finish. In this paper, an attempt was made to investigate the impact of process parameters of FSW in the mechanical properties of the joint. The tensile properties, microstructure, hardness of the FSW joints were investigated in the weldment and heat affected zone. The changes of mechanical properties are compared with the parental metal. The welding parameters such as tool rotational speed and welding speed plays a major role in deciding the joint characteristics. This paper focuses on optimization of all these parameters. From this investigation it was found that the joint made from the FSW yielded superior tensile properties and impact strength due to the higher hardness and fine microstructure.

Keywords
FSW, Welding Speed, Axial Force, Mechanical Properties, Microstructure

1. Introduction

In recent years, demands for aluminium alloy 6061 have steadily increased in aerospace, aircraft and automobile applications because of their excellent strength to weight ratio, good ductility, corrosion resistance and cracking resistance in adverse environment. Welding of these alloys, however, still remains a challenge. Apart from softening in the weld fusion zone and heat affected zone, hot cracking in the weld can be a serious problem [1]. Thus, the solid state bonding process is highly recommended to solve these problems. FSW is an innovative solid state welding process in which the metal to be welded is not melted rather the two parts of weld joints are brought into contact and the interface is strongly forged together under the effect of heavy plastic deformation caused by the inserted rotating stir probe pin [2].

In FSW a rotating cylindrical, shouldered tool with a profiled probe penetrates into the material until the tool shoulder contacts with the upper surface of the plates, which are butted together as shown in figure 1.

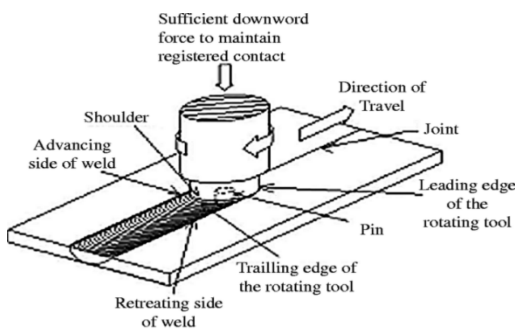

Figure 1.*Principle of FSW.*

The parts have to be clamped on to a backing bar in a manner that prevents the abutting joint faces from being forced apart. Frictional heat is generated between the wear resistant welding tool and the material of the work pieces. This heat causes the later to soften without reaching the melting point and allows traversing of the tool along the weld line.In FSW, tool rotation rate (rpm) in clockwise or counter clockwise direction and tool traverse speed (mm/min) along the joint are the most important parameters [3].

2. Literature Review

The effect of FSW parameters on temperature was examined by Muhsin et al .[4]. They concluded that the maximum temperature is a function of tool rotation rate while the rate of heating was a function of traverse speed.

Munoz et al. [5] investigated the microstructure and mechanical properties of friction stir welded and TIG welded Al-Mg-Sc alloy and reported that the yield strength FSW welded joint is decreased 20 % compared to base metal.

Apart from this, there have been lot of efforts to understand the effect of process parameters on material flow behaviour, microstructure formation and mechanical properties of friction stir welded joints. Finding the most effective parameters on properties of friction stir welds as well as realizing their influence on the weld properties has been major topics for researchers [6–8].

Extensive literature of friction stir welding of Al alloys does indicate that there are few areas particularly on the relationship between welding parameters and change in the mechanical properties of weldment. This paper focuses on finding the optimal speed (rpm) and feed rate (mm/s) with respect to mechanical properties such as hardness number and tensile strength.

3. Experimental Procedure

AA 6061 aluminum alloy chemical composition and mechanical properties are given in table 1 and 2 respectively.

Table 1.*Chemical composition in %wt.*

Name of the Al alloy	Mg	Si	Fe	Cu	Cr	Mn	Zn	Ti	Al
AA 6061	0.9	0.62	0.33	0.28	0.17	0.06	0.02	0.02	Balance

Table 2.*Mechanical properties.*

Name of the Aluminum alloy	Yield strength inMPa	Ultimate strength in MPa	Elangation %	Hardness in HV
AA 6061	110	207	16	75

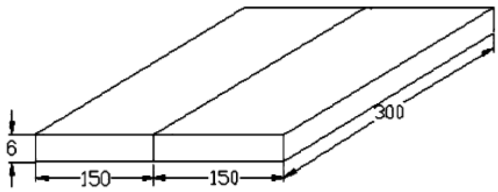

Fig 2.*Square Butt joint. (All dimensions are in mm)*

The rolled plates of AA6061 aluminium alloy were machined to the required dimensions (300mm X 150mm). Square butt joint configuration as shown in fig 2 was prepared to fabricate FSW joints. A non-consumable, rotating tool made up of high carbon steel was used. Probe diameter is 6 mm, shoulder diameter is 18 mm and pin length is 5.5 mm. FSW was carried out on a FSW machine manufactured by RV machine tools, India. Machine specifications are given in table 3.

Table 3.*Machine specifications.*

Spindle	ISO 40
Spindle speed	1000 to 3000 rpm (infinitely variable)
Z axis thrust	3000 to 10000 kgf
X axis thrust	1000 to 5000 kgf
Spindle motor	11 kW/440v, AC spindle servo motor
Version	CNC

The Aluminium plates are positioned in the fixtures, which is prepared for fabricating FSW joints by using mechanical clamps so that the plates will not separate during welding.

In present work, different FSW butt welds were obtained by varying tool rotation speed and welding speed with in the range obtained by the previous works [9,10] by keeping the axial force constant.

In this work FSW process was conducted with two variables: rotational speed(rpm) of the tool pin and traverse speed (mm/min) of the machine table. The rotational speed was chosen as: 720, 910, 1120 and 1400 rpm while the traverse speeds were 16, 20, and 31.5 mm/min.

4. Result and Discussion

A. Macro and Microscopic Visual Examination

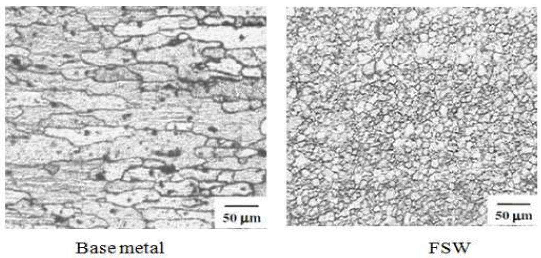

Fig 3.*Optical Micrographs of base metal and weldment.*

The optical microstructures of the base metal and weld centre are shown in fig 3.

Macroscopic visual examination of all welded specimens in transverse and longitudinal cross section showed defect-free sound weldments, produced under all applied experimental conditions. Uniform semicircular surface ripples in weld track were observed. These surface ripples, which have onion ringsconfiguration, were caused by the final sweep of the trailing edge of the continuously rotatingtool shoulder. A similar observation was made by many researchers [11-14].

Combined influence of temperature and plastic deformation induced by the stirring action causesthe recrystallized structure. In many FSW references on aluminum alloys, the initial elongated grains of the base materials are converted to a new equiaxed fine grain structure. This experiment confirms that behavior. The grain structure within the nugget is fine and equiaxed and the grain size is significantly smaller than that in the base materials due to the higher temperature and extensive plastic deformation by the stirring action of the tool pin. During FSW, the tool acts as a stirrer extruding the material along the welding direction. The varying rate of the dynamic recovery or recrystallization is strongly dependent on the temperature and the strain rate reached during deformation.

B. Hardness

Using Vicker's hardness testing machine hardness across the welds cross-section was measured. Hardness values are taken from weld face, midway through the weld nugget and near to the root of the FSW joint. The average values were plotted against the distance from the welding centre (fig 4).

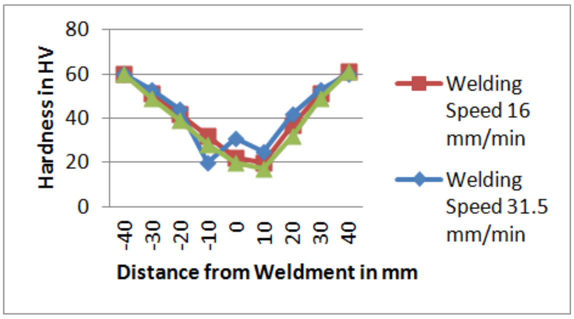

Fig 4. *Hardness Vs distance from weldment at 1400 rpm.*

Comparing with base metal hardness decreases towards the weld centre. This is due to the shear stress induced by the tool motion which lead to the generation of very fine grain structure as shown in fig 3. Dynamic recovery and recrystallization are the main softening mechanisms during FSW.When the average values of hardness in the welding centre were plotted against different tool rotation speed in fig 5, it was observed that when rotation speed increases more than 1200 rpm hardness in the weldment increases.This is because of the relatively high stacking fault energy which causes cross slip.This explanation was reached also by many researchers [15-19]. The result also reveals that 80-90% reduction in hardness comparing with base metal when traverse speed increases from 16 to 31.5mm/min.

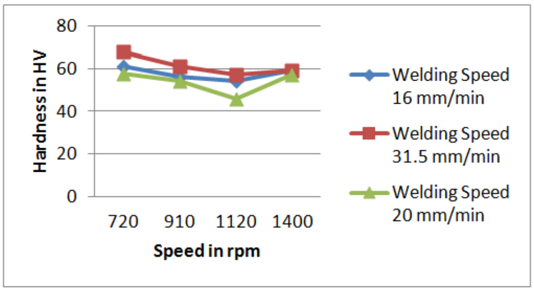

Fig 5. *Hardness VS speed.*

C. Tensile Properties

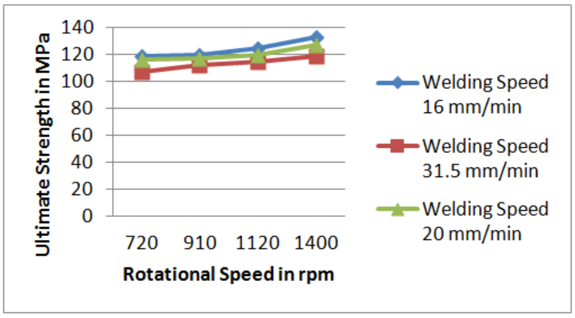

Fig 6. *Ultimate strength VS Rotational speed.*

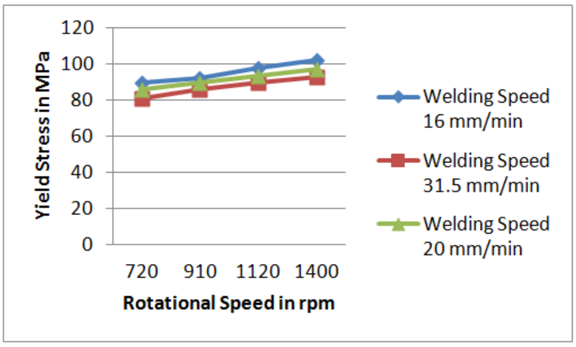

Fig 7. *Yeild strength VS Rotational speed.*

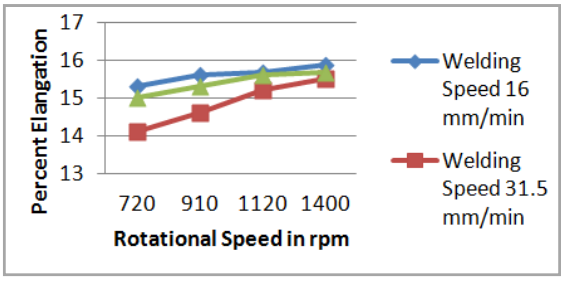

Fig 8. *Percentage Elongation VS Rotational speed.*

The transverse tensile properties such as yield stress, tensile strength and percentage of elongation of AA6061 aluminium alloy joints were evaluated. The measurements of ultimate tensile strength, yield stress and elongation for the welded specimen are shown in fig 6-8 respectively.The lowest ultimate tensile stress (UTS) found for welds in Al6061-T6 was 66% of the base material strength, while the highest yield strength found was over 90% of the base material strength. When the welding speed reduces, the specimen elongation in the weldment is nearly equal to the base metal.

5. Conclusion

In this paper, an attempt was made to investigate the impact of process parameters of FSW in the mechanical properties of the joint. From this investigation, the following conclusions have been derived: (i) The weld root surface of all the weldments showed visually a well joined defect free sound flat surface. (ii) The increase in stir–probe rotation speed more than 1200 rpm enhanced the weld soundness which may be a result of softening process associated with dynamic recovery and recrystallization process at the weld. (iii) The formation of fine equiaxed grains and uniformly distributed, very fine strengthening precipitates in the weld region are the reasons for the superior tensile properties of FSW joints.(iv) The width of the stir zone may depend on the balance between the total heat input and the cooling in the plasticized material. The area of the weld nugget zone size slightly decreased as the welding speed increased. Comparing with other welding speeds, the lowest speed 16mm/min results better mechanical properties and increase in the area of the weld nugget.

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