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Some investigations on mechanical and metallurgical properties of Friction Stir Welded joints of AA 6101 alloy

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ABSTRACT: *In 1991 a solid state joining process named friction stir welding was developed and this technique has attracted considerable interest from the aerospace and automotive industries, since it is able to produce defect free joints particularly for light and difficult to weld alloys i.e. magnesium and aluminum alloys. The selected material was welded using combination of different parameters i.e. tool rotational speed (900 rpm, 1400 rpm and 1900 rpm) and welding speed (20 mm/min, 35 mm/min and 50 mm/min). Tensile strength increases with the increase of welding speed from 20 mm/min to 50 mm/min. with increase of tool rotational speed from 900 rpm to 1400 rpm the ultimate tensile strength increases but at 1900 rpm the ultimate tensile strength decreases. The optimum value of tensile strength is 199 N/mm^2. The impact energies increases in friction stir welded material with respect to base metal and its optimum value is 39J. Microstructure reveals that the hardening precipitates more dissolves at welding speed of 50 mm/min and tool rotational speed of 1400 rpm as compared to other selected parameters.*

***Keywords**: Friction Stir welding, Mechanical Testing, Metallurgical Testing.*

I. INTRODUCTION

The working of Friction stir welding based on the principle that heat is generated primarily by friction [1] between a rotating-translating tools, the shoulder of which rubs against the work piece, thus plasticized material flows from advancing side to retreating side with help of rotational pin [2]. This welding technique involves the joining of metals without fusion or filler materials [3]. The tool has a circular section except at the end where there is a probe or pin. The junction between the cylindrical portion and the probe is known as the shoulder [4]. The pin penetrates the work piece whereas the shoulder rubs with the top surface. There is a volumetric contribution to heat generation from the adiabatic heating due to deformation near the pin. The welding parameters have to be adjusted so that the ratio of frictional to volumetric deformation induced heating decreases as the work piece becomes thicker. This is in order to ensure a sufficient heat input per unit length.

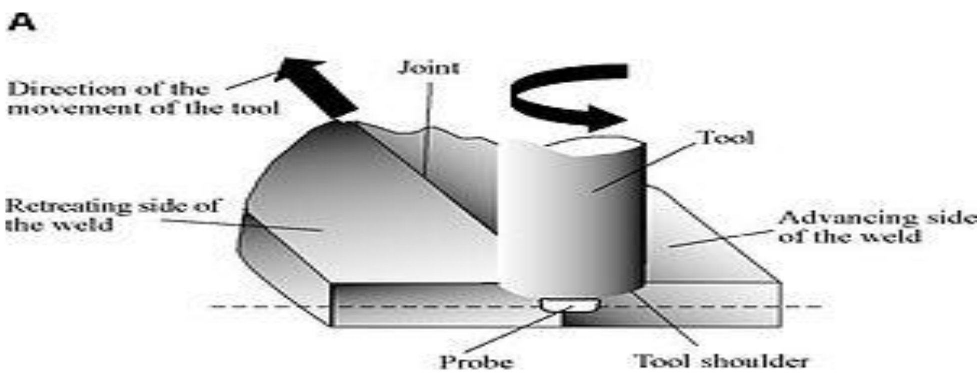

Figure 1. FSW operation [9]

Figure 1. illustrates an FSW operation, where the material to be joined is butted together end to end and clamped into a special designed fixture 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 material to soften [5] without reaching the melting point and allows transversing of the tool along the weld line. The maximum temperature reached is of the order of 0.8 of the melting temperature of the material. The plasticized material is transferred from the leading edge of the tool to the trailing edge of the tool probe and is forged by the intimate contact of the tool shoulder and the pin profile. It leaves a solid phase bond between the two pieces. The process can be regarded as a solid phase [6] keyhole welding technique since a hole to accommodate the probe is generated, then filled during the welding sequence. Notice that the two sides of the weld are named based on whether the side of the tool is rotating with the welding direction (advancing side) or against (retreating side). This nomenclature will be used throughout the study. An emerging and very attractive technology to overcome such drawbacks is FSW. FSW consumes less energy and leads to decrease in material waste and to the avoidance of radiation and dangerous fumes [7]. The energy efficiency, environment friendliness and versatility make the FSW a promisingly ecologic and "green technology".

III. EXPERIMENTATION

The material under investigation was a 6101 Aluminium alloy under the form of rolled plates of 5 mm thickness. Eighteen specimens of size 152 mm x 77 mm were welded together perpendicular to the rolling direction by Friction Stir Welding. Friction Stir welding of specimens were carried out by adopting three tool rotational speeds (900 rpm, 1400 rpm and 1900rpm) and three welding speeds (20 mm/min, 35 mm/min and 50 mm/min). A welding tool made up of High chrome high carbon steel with 20 mm tool shoulder diameter, 7 mm pin diameter and 4.8 mm long was used for welding. For Friction stir welding edges are finished with milling operation so that interfaces can be properly matched. The machine used for the production of joints was fully automated vertical milling machine. Fixture was first fixed on the machine bed with help of clamps and then plates were held in the fixture properly for Friction Stir Welding as shown in Figure 2.

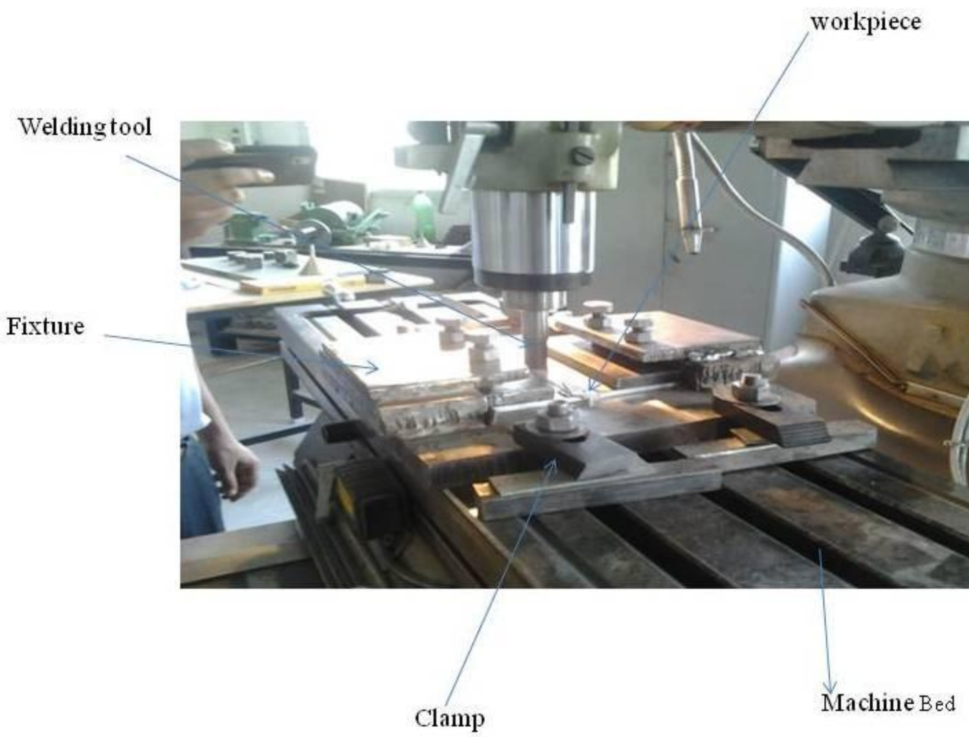

Figure 2. Work piece set up during FSW

Eighteen specimens of size 152 mm x 77 mm were welded together perpendicular to the rolling direction with Friction Stir Welding by adopting parameters given in Table no. 1

Table no. 1 Parameters used for Friction stir welding

Specimen no.	Welding Speed (mm/min)	Tool Rotational speed (rpm)	Tool shoulder Diameter (mm)
1	20	900	20
2	20	1400	20
3	20	1900	20
4	35	900	20
5	35	1400	20
6	35	1900	20
7	50	900	20
8	50	1400	20
9	50	1900	20

Specimens for the tensile strength analysis cut perpendicular to the weld line Tensile test specimens were prepared from each weld in accordance with ASTM specifications E-8M-08 as discussed by Inderjeet Singh et al. [8] having specimen of 50 mm gauge length and 12.5 mm width. 36 specimens were prepared from welded joints and 2 specimens were prepared from base material for tensile testing. Servo Control Universal testing machine was used for tensile testing. Tensile test was carried out at a constant speed of 2 mm/min at 16 kN load. The load was applied until the necking was there and specimen failed.

Figure 3. Specimens before testing

Specimens for microstructure testing were grinded on emery papers of grit size from 400 to 2500 for 3 to 5 minutes on each paper then polished on polishing papers of 3/0, 2/0 and 1/0 grade for 1minute to 3 minutes on disk polishing machine. After that specimens were polished on a velvet cloth separately with different grades (I, II and III) of alumina powder (Al_2O_3) for 2 minutes to 3 minutes. Etching (Methanol 25ml, Hydrochloric acid 25ml, Nitric acid 25 ml and Hydrofluoric acid 1drop), applied for 15 seconds. Visual inspection was performed on all welded samples in order to verify the presence of macroscopic external defects such as surface irregularities, excessive flash, and lack of penetration, voids and surface open tunnel defects.

IV.RESULTS AND DISCUSSION

The effect of selected friction stir welding parameters on mechanical and metallurgical properties have been discussed in detail along with their responding reasons and causes of occurrence of such characteristics in Friction stir welded Aluminium 6101 alloy joints.

A. Effect of welding speed on Tensile properties:

The effect of welding speeds 20 mm/min, 35 mm/min and 50 mm/min on tensile strength at optimized tool rotational speeds of 1400 rpm are represented in Figure 4.

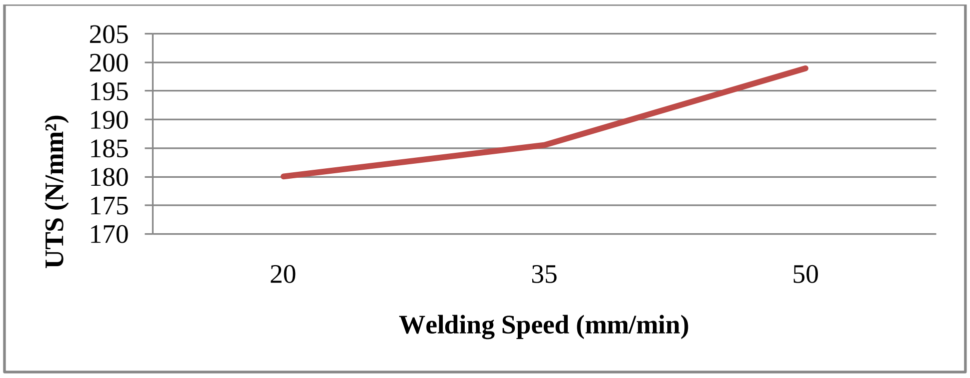

Figure 4. Effect of welding speed on tensile strength at 1400 rpm

As observed in Figure 4, UTS of welded joint was observed to be low at lower welding speed and increases with increasing welding speed from 20 mm/min to 50 mm/min. Due to high heat input at welding speed of 20 mm/min as compared to welding speed of 35 mm/min and 50 mm/min, there is more coarsening of grains in stir zone which is one of the reasons of lowering the UTS at welding speed of 20 mm/min. Grain boundaries were the main obstacles to slip of dislocations and material having smaller grain size and hence higher UTS as it would impose more restrictions to dislocation movement. The same findings were reported by Gurmeet Singh et al. [9]. With increase in welding speed the interaction between tool and work piece is improved. The same results are in consistent with the results reported by Gurmeet Singh et al. [10] and sufficient frictional heat generation per unit length causes better plastic flow of material at SZ which leads to higher UTS value at welding speed of 50 mm/min.

B . Effect of tool rotational speed on tensile properties

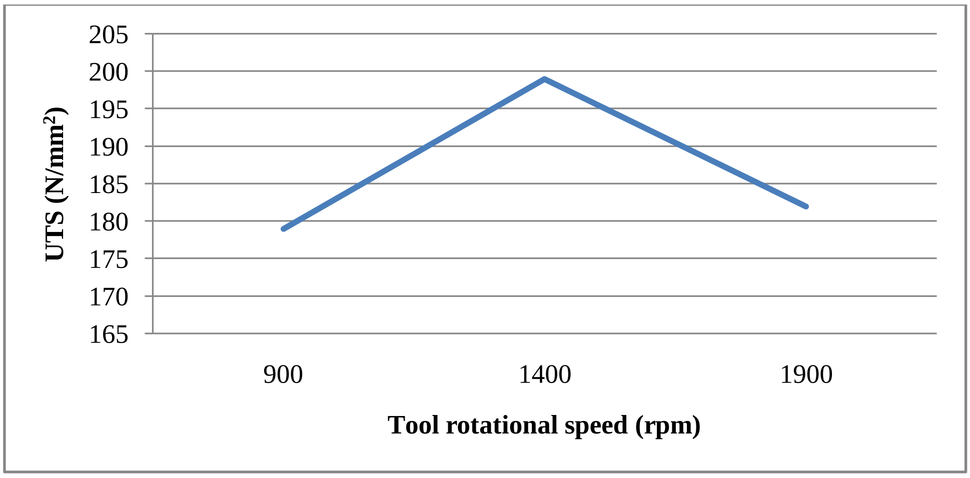

Figure 5. UTS at constant welding speed of 50 mm/min

As shown in Figure 5, it was revealed that there is a peak value of rotational speed from where the UTS starts decreasing with further increment in rotational rate due to high heat generation and insufficient material flow from AS to RS. These results are in consistent with results reported by Sundaram and Murugan [11]. UTS increase with increase in tool rotational speed from 900 rpm to 1400 rpm. The UTS values at 1400 rpm and 1900 rpm with above mentioned constant parameters are 199 N/mm^2 and 182 N/mm^2 respectively. Thus a decline in UTS value is observed at higher rotational speed, this is due to the fact that the higher rotational speed leads to high temperature near the threaded pin surface which would result in a higher probability for the occurrence of lack of bonding near bottom surface. The same findings were reported by Chouhan et al. [12]. Thus tunnel defects are observed at high tool rotational speeds due to insufficient material flow

C. Effect of FSW Process Parameters on Impact strength

Three specimens for each parameter were selected for impact testing and average values are presented in Table 2.

Table 2. Impact test results

Specimen no.	Welding Speed (mm/min)	Tool Rotational Speed (rpm)	Tool Shoulder Dia. (mm)	Energy absorbed in Joules
1	20	900	20	28
2	20	1400	20	26
3	20	1900	20	25
4	35	900	20	38
5	35	1400	20	29
6	35	1900	20	25
7	50	900	20	39
8	50	1400	20	33
9	50	1900	20	30

Impact toughness represents resistance of a material, in presence of notch and high strain rate loading. Friction stir welds in this research work showed a very interesting trend on impact toughness. Welds made by FSW process showed impact toughness values greater than those of the base material (in the range of 23 to 39 Joules). Ductile failures occurred in all the specimens and the failure location of all the joints was at the notch which was provided at the stir zone. Addition of silicon carbide during Friction stir welding improves the impact toughness.

D. Effect of tool rotational speed on impact strength

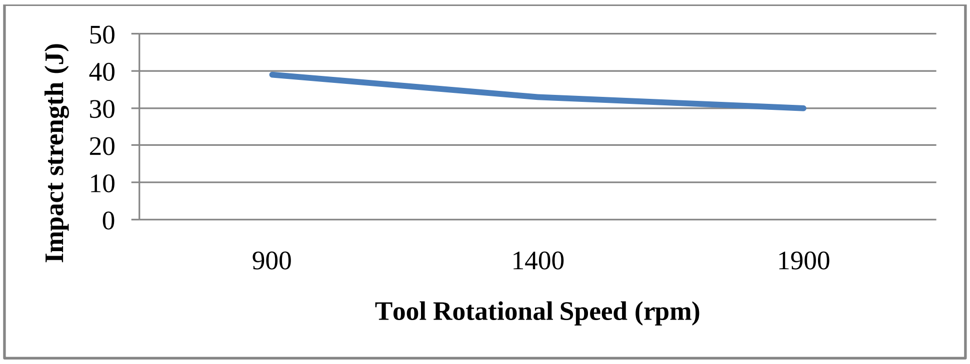

Figure 5. Effect of tool Rotational Speed on Impact Strength at 50 mm/min

As shown in Figure 5, with decrease in the tool rotational speed, impact toughness of weld joints improved, reaching maximum at the tool rotational speed of 900 rpm. When the tool rotational speed was increased, the heat input within the stir zone increased due to the higher friction. Higher heat generation causes slow cooling rate and this led to the formation of coarse grains in the SZ, which may be the reason of lower impact toughness at higher tool rotational speed

E. Effect of welding speed on impact strength

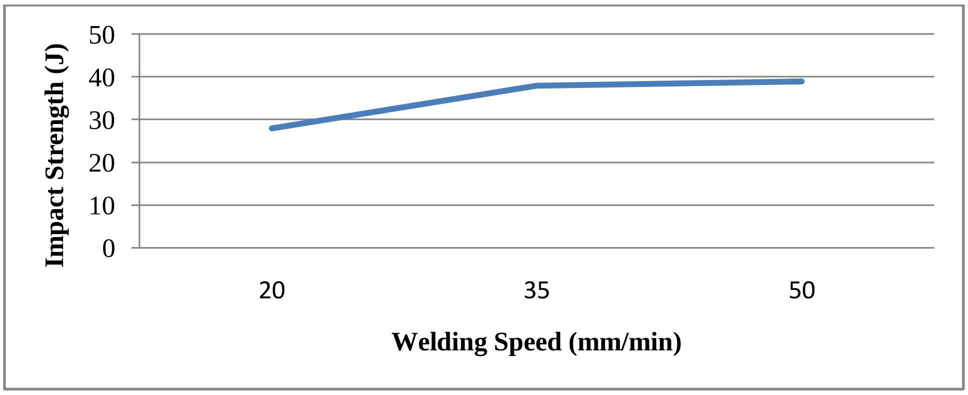

Figure 6. Effect of welding speed on Impact Strength at 900 rpm

As shown in Figure 6, with increase in welding speed the impact strength of welded joints is increased because of low heat input. Low heat input at high welding speed of 50 mm/min allows less time to grow and fine grains was achieved resulted in high impact strength.

F. Effect of FSW process parameters on microstructural properties

The typical microstructure of as received conditions (base material) is shown in Figure 7. The microstructure comprises of the coarse grains of aluminum with the hardening precipitates of Mg_2Si.

Mg_2Si (Hardening Precipitates)

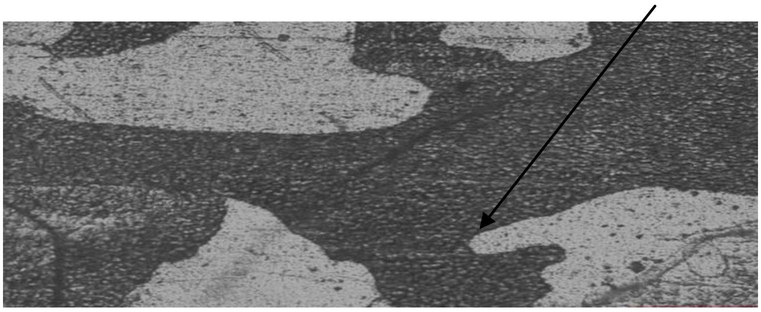

Figure 7. Microstructure (100X) of Base Material

G. Effect of Tool Rotational Speed on the Microstructure of Stir Zone

Figure 8, shows microstructure of Stir Zone of Friction stir welded joint sample fabricated with tool rotational speed of 900 rpm, 1400 rpm and 1900 rpm at constant welding speeds of 50 mm/min with 20 mm tool shoulder diameter.

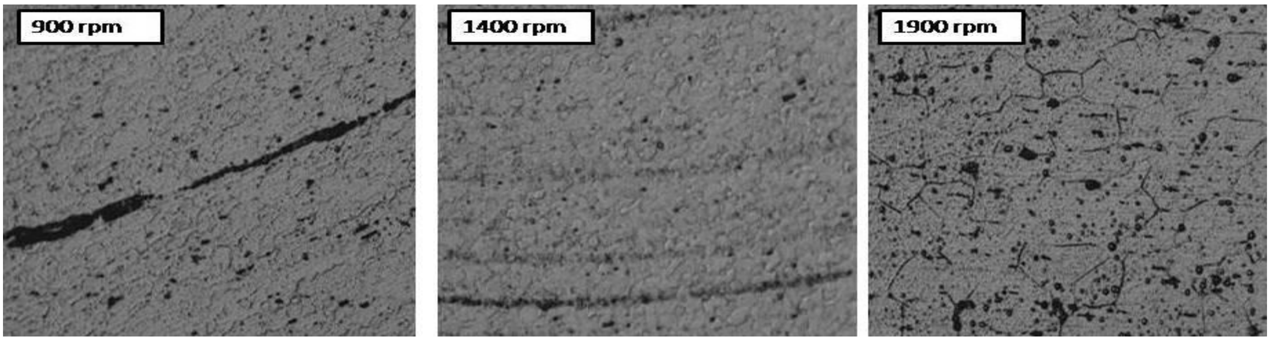

Figure 8. Micrographs (100X) of SZ at 50 mm/min welding speed

Hardening precipitates (Mg_2Si) dissolves more at tool rotational speed of 1400 rpm due to sufficient frictional heat generation during Friction Stir Welding. The same findings were reported by Miao and Laughin [13]. At tool rotational speed of 900 rpm dissolving of hardening precipitates is less because of insufficient heat generation and material flow that's why the tensile strength is less as compared to specimen welded at tool rotational speed of 1400 rpm. In this investigation it is observed that grain size of SZ increases with increasing rotational speed due to high heat input. Due to higher temperature achieved at 1900 rpm, the plasticized material takes long time to cool; hence enough time was available for grains to grow. The phenomenon of grain refinement has also been observed. The same results were reported by Patil and Soman [14]. Although higher tool rotational speeds leads to higher strain rates, which would have produced smaller grain size but the corresponding rise in temperature was found to have a more dominant effect on microstructure.

H. Effect of welding speed on microstructure of Stir Zone

Figure 9, shows the effect of welding speed on microstructure of Stir Zone of specimen welded at a constant tool rotational speed of 1400 rpm.

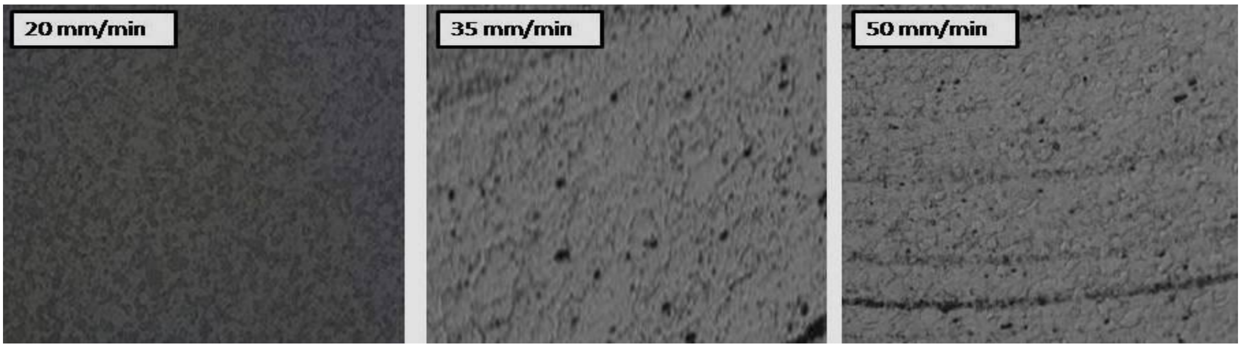

Figure 9. Micrographs (100X) of SZ at tool rotational speed of 1400 rpm

From Figure 9, it is revealed that the grain size of Stir Zone of Friction Stir Welded joint was the function of welding speed, it decreases with increase in welding speed due to low heat input which reduces time for grain growth to grow. Due to material deformation caused by tool shoulder and pin, the mixing of material flows associated with pin and shoulder leads to grain refinement.

V. CONCLUSIONS

The mechanical properties and the resultant microstructure for friction stir welded Aluminium 6101 alloy were presented for different combinations of tool rotational speeds and welding speeds. The correlation of mechanical properties and microstructure with the process parameters for the optimization of process is a unique approach which has been the main motivation behind this research. Following conclusions were derived from the results of this experimental work.

- Tensile Strength increases with the increase of welding speed from 20 mm/min to 50 mm/min. With increase of tool rotational speed from 900 rpm to 1400 rpm the ultimate Tensile strength increases but at 1900 rpm the ultimate tensile strength decreases
- The hardening precipitates are more dissolved at welding speed of 50 mm/min and tool rotational speed of 1400rpm as compared to other selected parameters. Refinement of grain structure at Stir Zone is achieved after Friction Stir Welding.
- Improvement in Impact energies is observed in friction stir welded joints of AA 6101 alloy with respect to base metal

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