

# An Experimental Study of Mechanical Properties and Effect of Welding Speed of Friction Stir Welding on Aluminium Alloy 6061

N. Dilip Raja, R. Velu and S.T. Selvamani\*

Department of Mechanical Engineering, Vel Tech Multi Tech Dr. Rangarajan Dr. Sakunthala Engineering College, Avadi, Chennai – 600062, Tamil Nadu, India; dilip\_raja10@yahoo.co.in, veluramasamy@gmail.com, selva\_balu@rediffmail.com

## Abstract

Friction Stir Welding is a versatile metal joining process, which has been adopted to join composite materials. Many research activities have been conducted on this metal joining processes which lead to the process being used in diverse field of applications. AA6061 plates of 6mm thick each were joined through butt welding configuration by Friction Stir Welding process using a CNC milling machine and a non consumable tool with square pin profile. Six joints were made using the combination of three tool rotation speed 350 rpm, 550 rpm and 900 rpm and three weld traverse speed 55 mm/min, 100 mm/min, 110 mm/min. The prepared joints were tested in order to analyze its microhardness, tensile strength, temperature distribution, force and microstructure along the joint. It was identified that for a given tool rotation speed, the microhardness increased proportionally with respect to the weld speed and depth along the joint. However it was noticed that for different tool rotation the maximum of the microhardness was obtained for 350 rpm. Measurement of tensile strength revealed that the strength was maximum when the weld speed and tool rotation speed was maximum. The tensile strength measurement indicated that the strength was directly proportional to the weld speed and tool rotation speed. Temperature measured during welding revealed that the temperature was maximum along the weld center, while same decreased away from the weld center. This was because of the dissipative effect of AA6061. Microstructure of the prepared joint revealed that the due to the influence of the tool, the grain structure reformed. There were finer grains at place traversed by the tool and coarse grains at place away from the tool. The joints thus fabricated can be used for applications which require reliable and defect free joints such as automobile frames and aeronautical structures.

**Keywords:** AA6061, Friction Stir Welding, Microhardness, Microstructure, Temperature distribution

## 1. Introduction

Friction Stir Welding (FSW) is a derivative of a conventional friction welding process. In friction-stir welding process, a welding-head pin rotating in excess of a few hundred rpm, travels down the length of contacting metal plates, creating a highly plastically deformed zone through the associated force and frictional heating. This plastic deformation zone is essentially stirred into a solid-phase weld on the trailing side of the welding head pin. This process can be simulated in a solid metal plate by simply advancing

the rotating head pin into the work piece, with a residual weld zone forming on its trailing side<sup>1</sup>.

The Principle of working is shown in Figure 1. This rotating tool penetrates the firmly clamped work pieces at a certain RPM and further move along the desired joint line produces a high integrity, defect free weld. The quality of joint needs the attention of carefully chosen process parameters namely, tool RPM, welding speed, shoulder and pin diameters and profile among others. The rotating and translating motion of the tool cause intense plastic straining of the material resulting in extremely fine

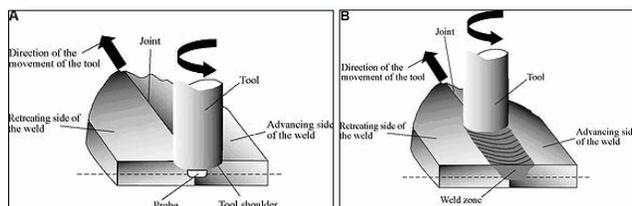
\*Author for correspondence

grain size in the stirred zone or weld nugget<sup>2</sup> as shown in Figure 2.

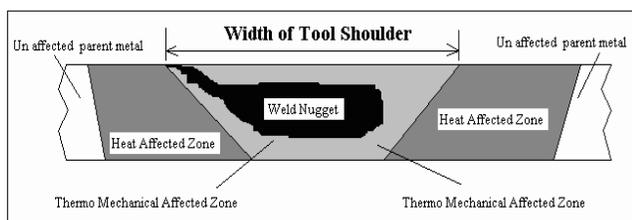
The difficulty and subsequent defects of making high-strength, fatigue and fracture resistant welds in aerospace aluminum alloys, such as highly alloyed 2XXX and 7XXX series, has long prohibited the wide use of welding for joining aerospace structures. These aluminum alloys are generally classified as non-weldable since there is poor solidification microstructure and porosity in the fusion zone<sup>3</sup>.

Defect free welds with good mechanical properties have been made with a variety of aluminum alloys, even though previously it was thought to be not weldable. When alloys are friction stir welded, phase transformations that occur during the cool down of the weld are of a solid state type. Due to the absence of parent metal melting, the FSW process is found to offer several advantages over fusion welding<sup>4,5</sup>.

In FSW, a cylindrical-shouldered tool, with a profiled threaded probe (nib or pin) is rotated at a constant speed. It is fed at a constant traverse rate into the joint line between two pieces of plate material, which are butted together. The parts have to be clamped rigidly onto a backing bar in such a manner that prevents the abutting faces from being moved apart. The length of the nib is slightly less than that



**Figure 1.** Schematic of the FSW process: (a) Two discrete metal pieces butted together, along with the tool (with a probe). (b) The progress of the tool over the length of the joint, showing the weld zone and the region affected by the tool shoulder.



**Figure 2.** A schematic of different regions of FSW.

of the weld depth required and the tool shoulder should be in intimate contact with the work piece surface. The nib is then moved against the work, or vice versa<sup>6</sup>.

Due to friction heat is generated between the wear-resistant welding tool shoulder and nib, and the material of the work pieces. This heat, along with the heat generated by the mechanical mixing process and the adiabatic heat within the material, causes the stirred metal to soften without reaching the melting point, allowing the traversing of the tool along the weld line in a plasticized tubular shaft of metal, and hence it is called solid state welding process. As the pin moves in the direction of welding, the leading face of the pin, assisted by a special pin profile, forces plasticized material to the back of the pin while applying a substantial forging force to join the weld metal. The welding of the material is carried out by severe plastic deformation in the solid state, involving dynamic recrystallization of the base material<sup>7</sup>.

Six important welding parameters are considered for studying the frictional stir welding processes. These are tool rotation and traverse speeds, tool tilt and plunge depth, tool design, welding forces, flow of material, and generation and flow of heat<sup>8</sup>.

There are three factors that determine joint characteristics obtained by friction stir welding. They are pin rotation speed, pin welding speed and pin depth of sinking. Pin rotation speed and welding speed can be controlled easily. But, pin depth of sinking is so critical factor and difficult to controlled. The depth of sinking must be constant all over the welding process. But, it is not possible to provide especially in joint process of long plate, unless surfaces are smooth. Therefore, preparation of surfaces before welding is very important<sup>9</sup>.

## 2. Experimental Procedure

The material used in this study is AA 6061, a precipitation hardened aluminium alloy containing silicon and magnesium as major alloying elements<sup>10</sup>. It is produced by die casting using induction furnace and extruded into as required dimension (5 x 100 x 300 mm from 6 x 100 x 250 mm) with a heat treatment to T6 temper condition. The chemical composition of the aluminium alloy is furnished in Table 1.

The FSW machine used in this experimental study was manufactured by HMT Technologies. The machine has three axes, X; perpendicular to the tool axis in the direction of toward welding, Y; perpendicular to the tool axis

**Table 1.** Chemical composition of aluminum alloy AA 6061

Aluminium Alloy 6061								
Element	Cu	Mg	Mn	Fe	Cr	Ni	Si	Al
Amount %	0.21	0.86	0.02	0.14	0.007	0.008	0.46	Bal

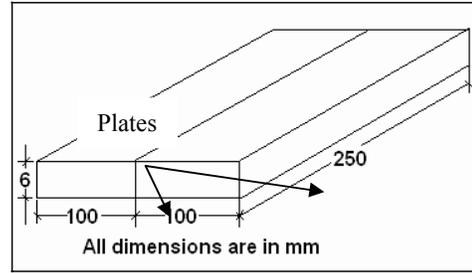
in the direction of towards welding and perpendicular to X axis and Z; parallel to the tool axis and in the plunge direction, It is a CNC displacement control milling machine with a maximum continuous power of 15 kW, Table size, 305 mm X 1250 mm, and maximum speed is 1500 rpm.

The total weld length created was around 150 mm from the pin entry to the pin exit. The pin was inserted at 25 mm from the leading plate edge and was extracted at 200 mm. FSW tool was machined from high carbon tool steel with a hardness value of 55 HRC. A double step pin was used, whose geometrical characteristics are shown in Figure 3.

The square butt joints were prepared to fabricate FSW joints. The configuration is shown in Figure 3.

FSW joints were made by joining two plates. Welding was performed perpendicular to the rolling direction with a backward tool. AA6061 plates along with a steel backing plate were clamped firmly onto the load measuring device, in order to prevent the abutting faces from being forced apart. It is shown in Figure 4. The device in turn was placed on machine bed with stainless steel bright rods in between. Its movement is restricted in three planar directions whereas the unrestrained positive X direction movement allowed the measurement of the X-direction force. Lab VIEW (Laboratory Virtual Instrumentation Engineering Workbench), a visual programming language from National Instruments, was used to construct a program to interface the load measuring device via a PCL 818HG data acquisition card.

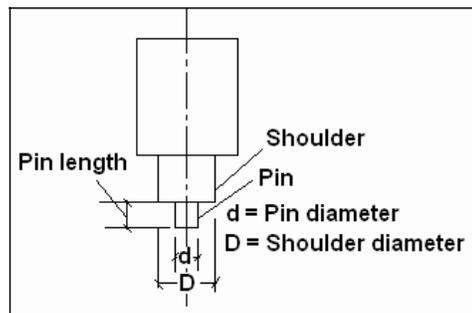
The experiments were conducted with variation of welding speed while other parameters namely tool RPM, shoulder diameter and pin diameter and same profile were recorded. Three runs were carried for each parameter combination. The total weld length was around 150 mm from pin entry to pin exit. FSW tool was machined from square tool with a measured hardness value of 55 HRC. A two step pin was used. The geometrical characteristics of the pin are shown in Figure 5.



**Figure 3.** Configuration of tools.



**Figure 4.** Laboratory Virtual Instrumentation Engineering Workbench (Lab VIEW).



**Figure 5.** Configuration of the weld joint specimen.

### 3. Results and Discussion

An attempt was made to study the effect of tool pin profile and welding speed on the formation of friction stir welding. During comparison, a microhardness and microstructure of FSP reigns produced by square pin profile tool was better than the other profile. The weld also exhibited maximum tensile strength, higher hardness and fine grains in the FSP reign<sup>11</sup>.

The tool used for the experiment was essentially a two step tool designed so as to provide appropriate material movement. The weld parameters and designations are given in Table 2.

**Table 2.** Weld parameters

S. No	Parameter	Value
1	Shoulder diameter	25 mm
2	Pin diameter (square)	12 mm
3	Tool speed	350 rpm, 550 rpm and 900 rpm
4	Weld speed	55 mm/min, 100 mm/min, 110 mm/min

### 3.1 Effect of Microhardness

To find the microhardness, Vickers microhardness test was carried out with a 100 N load and 15s dwell time. Three rows of indents, 0.5, 2.5 and 4.5 mm from the top surface were made along the cross section of the weld, using a semi-automatic micro-hardness tester. The Vickers indents were made with a spacing of 0.3 mm and were used to quantify the effect of heat input during the welding process. The hardness test was carried out in accordance to the standard ASTM E384<sup>12</sup>.

The comparison between microhardness and weld speed along the weld joint is shown in Table 3 to Table 5. Table 3 shows the respective values when the weld was made at 350 rpm tool speed. Table 4 shows the same kind of comparison when the weld was carried out at 550 rpm tool speed. Similarly Table 5 shows the relationship between microhardness along the weld joint and weld speed when it was made at 900 rpm. It was observed that there was no appreciable change in the microhardness readings along the weld. Figure 6 to Figure 8 shows that there is no adverse effect of the welding process on the microhardness. Microhardness remains always constant throughout. It can also be seen that when the feed rate of the tool is increased, microhardness increased.

### 3.2 Effect of Tensile Test

To determine the mechanical properties of the fabricated weld joint, a tensile test was performed according to EN 895 by preparing three test specimens<sup>13</sup>. The details of the test specimen are given in Figure 9.

The average tensile strength versus tool speed is given Figure 10. The results of the tensile test are shown in Table 6. It is observed that the weld joint mechanical properties improve and the appearance gets better if weld speed is raised to 900 rpm and feed to 110 mm/min. The weld joint breakage occurs either in stirred welding zone or heat affect zone. It was found that weld joint tensile properties are satisfactory, though not comparable with base metal.

**Table 3.** Microhardness along the weld joint for different weld speeds at tool rotation of 350 rpm

Weld Speed (mm/min)	Location of the indent from the top (mm)			Microhardness (HV)
	0.5	2.5	4.5	
55	74.2	76.8	75.4	
100	77.6	80	82.2	
110	82.4	84.4	86.5	

**Table 4.** Microhardness along the weld joint for different weld speeds at tool rotation of 550 rpm

Weld Speed (mm/min)	Location of the indent from the top (mm)			Microhardness (HV)
	0.5	2.5	4.5	
55	62.5	65.5	68.2	
100	66.7	70.2	70.1	
110	70	72.3	75	

**Table 5.** Microhardness along the weld joint for different weld speeds at tool rotation of 900 rpm

Weld Speed (mm/min)	Location of the indent from the top (mm)			Microhardness (HV)
	0.5	2.5	4.5	
55	66	69.8	70.2	
100	68	70.1	74.4	
110	70.3	75.9	77.8	

### 3.3 Temperature Distribution

FSW results in intense plastic deformation around rotating tool. The temperatures obtained during the welding process are analyzed. Friction between tool and work pieces raises the heat. Both these factors contribute to the temperature increase within and around the stirred

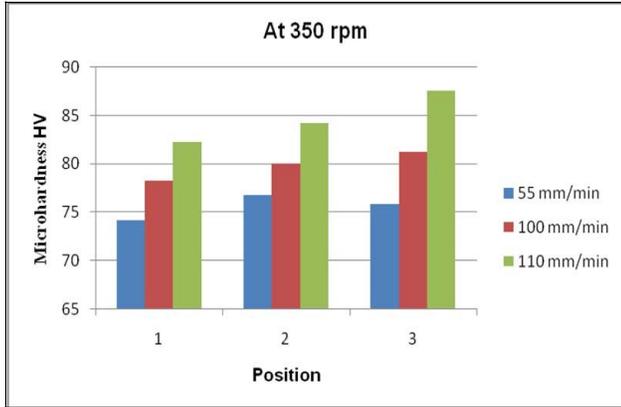


Figure 6. Effect of Microhardness at tool speed 350 rpm.

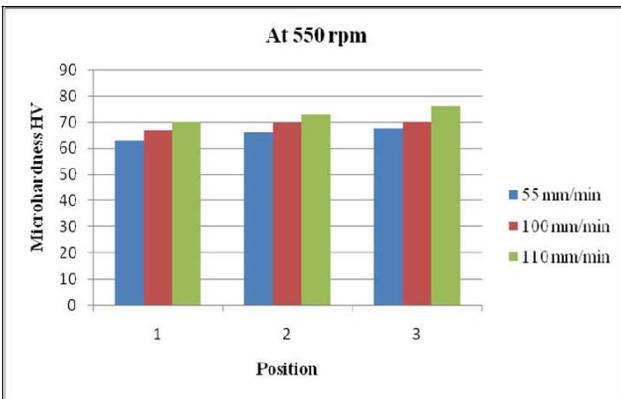


Figure 7. Effect of Microhardness at tool speed 550 rpm.

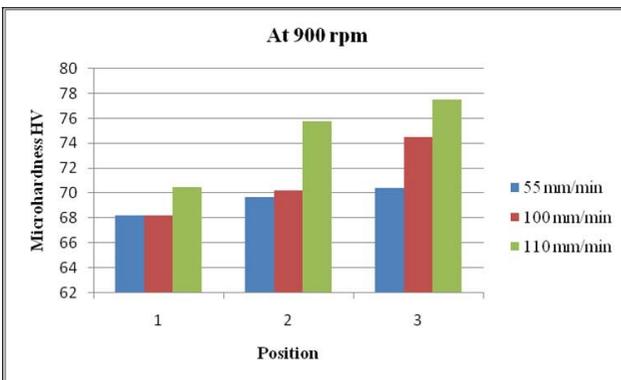


Figure 8. Effect of Microhardness at tool speed 900 rpm.

zone. The temperature measurements within the stirred zone are very difficult due to the intense plastic deformation produced by the rotation and translation of tool. Therefore, the maximum temperature within the stirred zone during FSW was estimated from an embedded thermocouple in the regions adjacent to the rotating pin. The

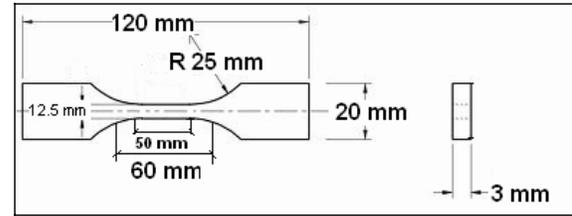


Figure 9. Dimension of the tensile test specimen.

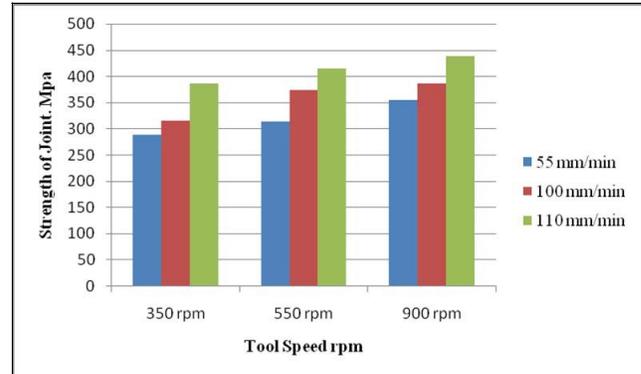


Figure 10. Tensile strength of MMC at different welding speed and tool speed.

Table 6. Joint strength versus tool speed and weld speed

Weld Speed (mm/min)	Tool speed (rpm)			Joint strength (MPa)
	350	550	900	
55	290	310	355	Joint strength (MPa)
100	314	353	374	
110	380	415	440	

Figure 11 shows the peak temperature distribution adjacent to the stirred zone and edge of the stirred zone. The temperature decreased with increasing distance from the stirred zone as expected. The temperature at the edge of the stirred zone increased from the bottom surface of the plate to the top surface. The maximum temperature was recorded near the corner between the edge of the stirred zone and the top surface. The obtained values are shown in Table 7.



**Figure 11.** Feed rate on peak temperature for constant speed at 550 rpm.

**Table 7.** Feed rate on peak temperature for constant speed at 550 rpm

Weld Speed (mm/min)	Distance from weld centre (mm)						Temperature (°C)
	0	2	4	6	8	10	
55	420	410	400	380	380	370	Temperature (°C)
100	450	420	410	395	390	375	
110	490	470	460	450	420	410	

### 3.4 Effect of Forces against the Tool

The effects of forces at pin rotating speed of 550 rpm and weld feed 55, 100, 110 mm/min are furnished here. The force acts against the pin due to normal force acting on tool. It affects the motor and the bed of milling machine. In this experiment the special attachment was designed and developed for finding the force acting against the tool<sup>14</sup>. It is shown in Figure 12.

Force along X axis; increase is acceptable as more material is to plasticized

Force along Y axis; increase is acceptable as time per unit length decreases. Therefore the heat input per unit length also decreases.

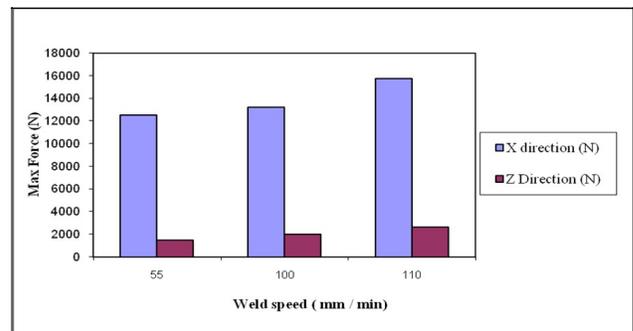
### 3.5 Microstructural Analysis

Friction Stir Welding is typically composed of a fine-grained dynamically recrystallized weld nugget (WN), which refers to the area previously traversed by the tool pin. The WN itself lies within the Thermo-Mechanically Affected Zone (TMAZ), which is a trapezoidal region whose upper base

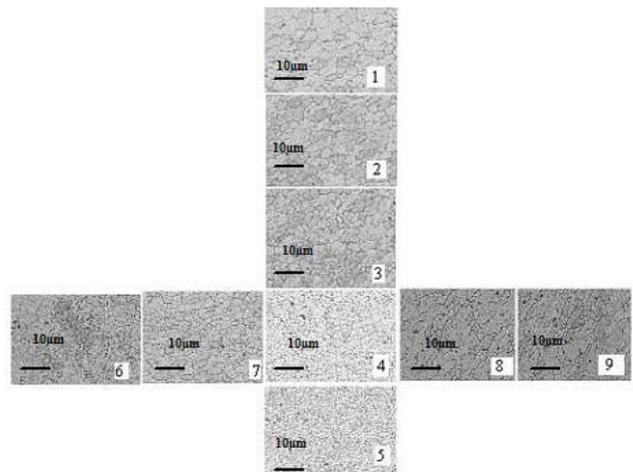
is the diameter of the tool shoulder and its lower base is slightly larger than the pin diameter. The Heat Affected Zone (HAZ) surrounds the TMAZ on both shoulders. The HAZ is believed to be unaffected by any mechanical effects, but affected by the heat generated by the friction effect associated by the shoulder and tool pin rotation<sup>15</sup>.

Several images were taken from different zones of the welding in order to determine the microstructure of the welded zone. Fig 13 shows some of such images. The weld exhibits an equated grain structure in the weld nugget. Observing the images of Figure 13, from 1 to 5 it can be observed that the grain size tends to decrease from the top to the bottom of the specimen.

When observed the middle lines (points 3 and from 6 to 9) offers some remarks. When examining images from position 3, 7 and 8, it can be seen that there is not much difference in the appearance of the samples. The grain size is quite alike.



**Figure 12.** Effect of force acting on the tools.



**Figure 13.** Grain size and distribution on vertical traverse cross-section in 2219-T87 FSW nugget section 500x.

At positions 6 and 9, in the edge of the welding tool's pin, an abrupt transition from the highly refined, equated, grains making the nugget zone to deformed base material grains occurs.

When analyzing other areas from the fracture surface, it can be seen that the existence of other inclusions in the welded material. The Figure 13 shows a hole left by one of these inclusions. The walls of the hole are quite flat, which contrast with the rest of the fracture surface, consistent of micro voids. Being a solid state process, no external inclusions can be accounted for. The presence of these holes can be attributed to agglomerated  $\theta$  particles and the results are consistent with finding of Kuo et al<sup>16</sup>.

## 4. Conclusions

An in depth analysis of the mechanical behavior of a welded joint of aluminium alloy 6061 fabricated by FSW technique was carried out. With increasing weld speed the heat input per unit length decreased leading to increased stress on the machine as seen from the increased welding process parameters.

The joints show excellent mechanical properties like microhardness and tensile strength. There was no appreciable change in the micro hardness along the weld. The resulting microstructure has shown a new equated fine grain size structure. An abrupt transition from the highly refined, equated, grains comprising the nugget zone to deformed base material grains occurred.

## 5. Acknowledgement

The authors wish to express their sincere thanks to Prof. S. Sunil Pandey, Indian Institute of Technology, New Delhi for permitting us to conduct experiments.

## 6. References

1. Anderson T. Alco Tec Wire Corporation, USA, The advancement of aluminum within the welding fabrication industry and its many product design applications. *A Welding Review: ESAAB*. 2000; 54 (2):3–5.
2. Shukla RK, Shah PK. Comparative study of friction stir welding and tungsten inert gas welding process. *Indian Journal of Science and Technology*. 2010; 3(6):667–71.
3. Mani A, Pandey S. Study of Microhardness Friction Stir Welded of Aluminium Alloy 6120, *Welding Workshop at Longowal*; 2004. p. 124–31.
4. Mishra RS, Ma ZY, Friction stirs welding and processing. *Materials Science and Engineering*. 2005; R50:1–78.
5. Threadgill PL. Friction stir welding: the state of the arts. *Bulletin 678*, TWI, UK; 1999.
6. Kallee SW. Friction Stir Welding at TWI. *The Welding Institute (TWI)*; 2006.
7. Leonard AJ. Microstructure and aging behavior of FSW in Al alloys 2014A-T651 and 7075-T651, 2nd International Symposium on FSW (CD ROM); Gothenburg, Sweden: 2000.
8. Nicholas ED. Developments in the friction-stir welding of metals. *ICAA-6 6<sup>th</sup> International Conference on Aluminum Alloys*; Toyohashi, Japan: 1998.
9. Hemath Kumar G. Indian Institute of Technology, New Delhi; 2007. p. 1–343.
10. Dawes J, An Introduction to Friction Stir Welding and its Development, *Welding. Metal Fabrication*. 1996; 61(1):61–8.
11. Murr LE, Liu G, McClure JC. Dynamic re-crystallisation in the friction-stir welding of aluminum alloy 1100. *Journal of Materials Science Letters*. 1997; 16(22):1801–3.
12. Meran C. The joint properties of brass plates by friction stir welding. *Materials and design*. 2006; 27 (9):719–26.
13. Sutton MA, Yang B, Reynolds AP, Taylor R. Microstructure studies of friction stir welds in 2024-T3 aluminium. *Materials Science and Engineering*. 2002; 323(1-2):160–6.
14. Yang B, Yan J, Sutton MA, Reynolds AP. Banded microstructure in AA2024-T351 and AA2524-T351 aluminium friction stir welds, Part I. Metallurgical studies. *Material Science and Engineering*. 2004; A364(1-2):55–65.
15. Suresh Babu A. Devanathan C. An Overview of Friction Stir Welding. *IJRMET*. 2013; 3(2):259–65
16. Feng Z, Santella ML, David SA, Steel RJ Packer SM, Kuo M, Bhatnagar RS. Friction Stir Spot Welding of Advanced High-Strength Steels – A Feasibility Study, *SAE Technical paper*; 2005. p. 1–1248.