1. INTRODUCTION:

Friction stir processing is a generic metallurgical tool for microstructural modification. The adaption of these friction stir process based technological variants is slow but the potential of these is limitless. FSP is a method of enhancing the properties of metal through intense, localized plastic deformation by optimizing the process parameters such as rotational speed, traverse speed, plunge depth, axial forces. It was invented at the welding institute of UK in 1991[1]. The intrinsic nature of FSP has two basic components material flow and microstructural evolution. In friction stir processing super plasticity of material is important factor. Superplasticity is an ability of a material to exhibit >200 % elongation in tension. The most important microstructural features that govern the overall superplastic behavior are as follows:

(a) fine grain size (<15 μm),

(b) equiaxed grain shape,

(c) presence of very fine second phase particles to inhibit grain growth, and

(d) large fraction of high angle grain boundaries[2].

1.1 Problem Statement:

"Optimization of process parameters of additive friction stir processing of 7075 aluminium alloy for defence application."

1.2 Objectives:

After finding research gap in additive Friction Stir Processing process from surface modification point of view, following research objectives has been finalised.

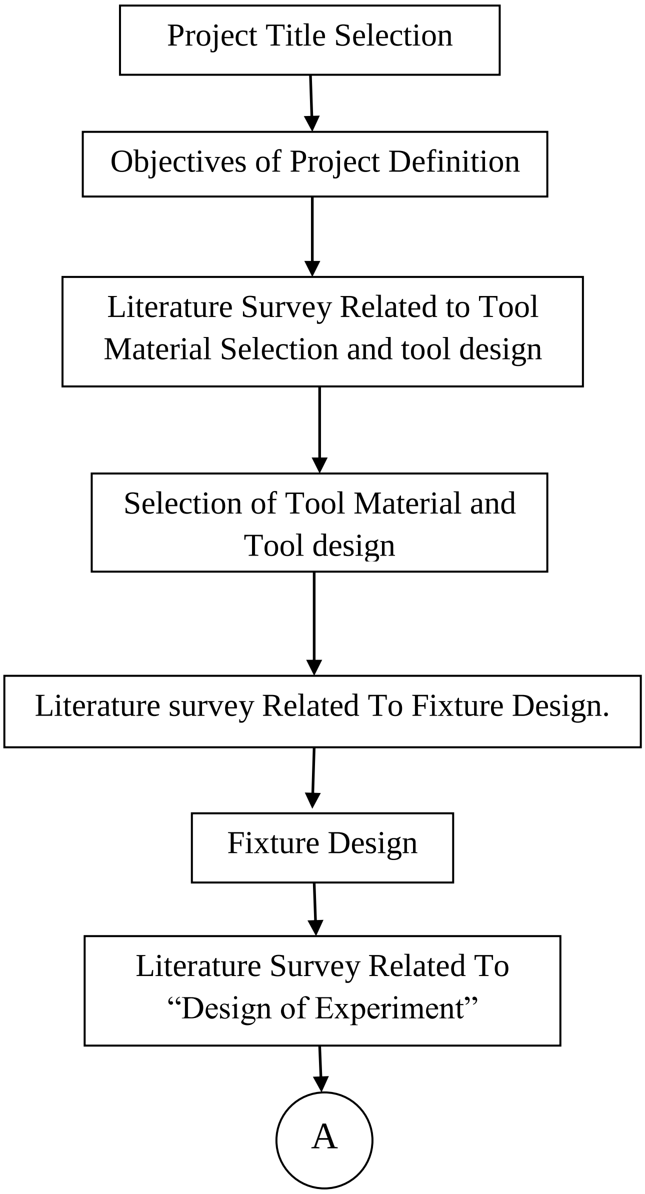
- To optimize combined process parameters so as to get best possible grain refinement.
- Design and conduct FS processing experiments on aluminium alloy for different combinations of rotational and translational speeds.

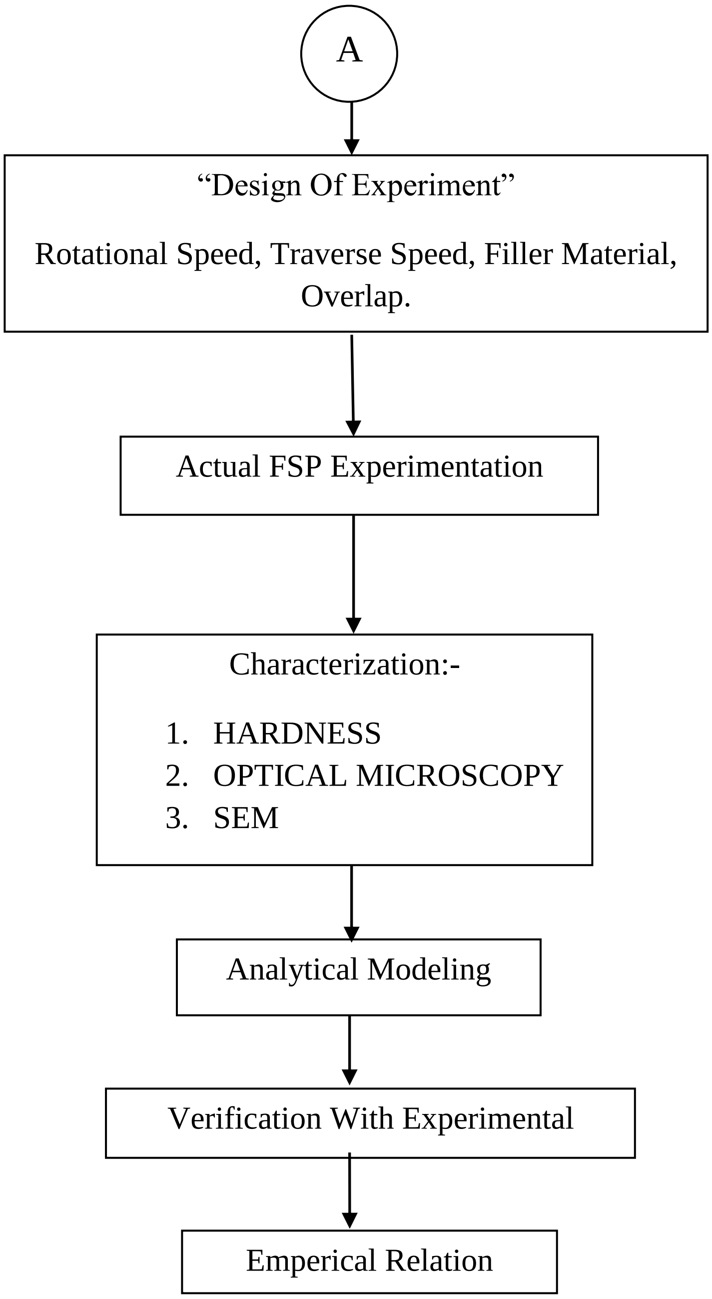
1.3 Scope:

In earlier days steel was used for construction of tank which are used in battle field. Due to the high density of steel tanks, the weight of these tanks also increased. Due to this disadvantage, metals consisting of low weight to strength ratio were introduced.

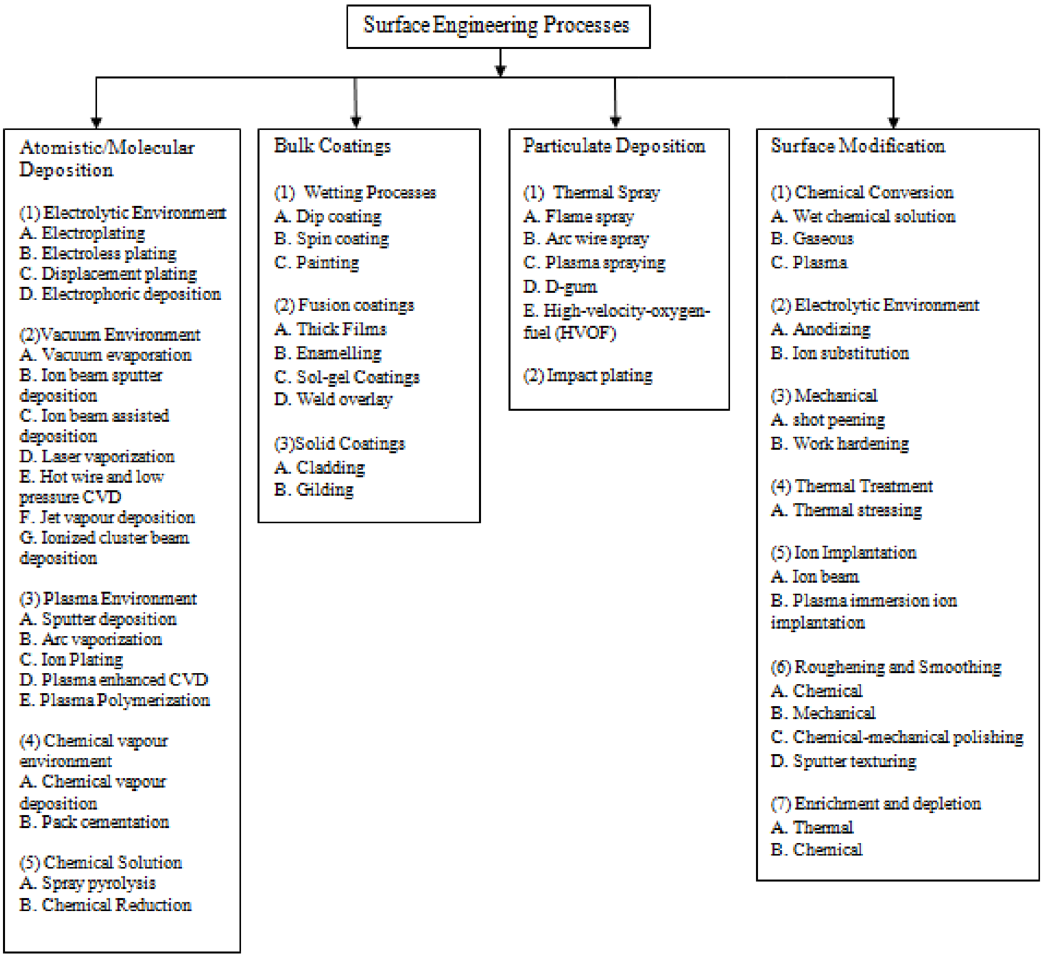
Consisting with such metal property many metals came into picture such as aluminium, titanium, copper etc. Amongst these, aluminium 7075 alloy was best suited for the defence application due its properties such as high strength and low weight. But tanks require high ballistic performance and wear resistance, which is not seen in abundance in Al 7075 alloy. Hence to obtain required properties surface enhancement is essential which is carried out by additive friction stir processing. Including defence applications such as tank manufacturing and armour manufacturing, FSP is also used in many other applications such as aerospace, automobile etc.

1.4 Methodology:




A
“Design Of Experiment”
Rotational Speed, Traverse Speed, Filler Material, Overlap.
Actual FSP Experimentation
Characterization:-
1. HARDNESS
2. OPTICAL MICROSCOPY
3. SEM
Analytical Modeling
Verification With Experimental
Emperical Relation

1.5 Classification of Various Surface Engineering Techniques are as follows:



1.6 Why FSW/FSP?

- Friction Stir Processing (FSP) is one of new and promising thermo mechanical processing techniques that alters the microstructural and mechanical properties of the material in the single pass to achieve maximum performance with low production cost in less time with the simple and less expensive tool.
- Preliminary studies of different FS processed alloys report the processed zone to contain fine grained, homogeneous and equiaxed microstructure.
- The potential applications of FSP is in superplastic forming (SPF), which is a net shape forming technique.

- Superplasticity is a phenomenon exhibited by fine-grained material during which these materials exhibit an elongation of more than 200% under controlled conditions.

1.7 Severe Plastic Deformation:

FSP works on the principle of sever plastic deformation. Processes of severe plastic deformation (SPD) are defined as metal forming processes in which a very large plastic strain is imposed on a bulk process in order to make an ultra-fine grained metal. The objective of the SPD processes for creating ultra-fine grained metal is to produce lightweight parts by using high strength metal for the safety and reliability of micro-parts and for environmental harmony.

1.8 Friction Stir Welding:

Friction stir welding is a solid state joining process that uses a non-consumable tool to join two facing work pieces without melting work piece material. Friction stir welding is a most efficient process among the other welding processes. . It was invented in 1991 at The Welding Institute (TWI). It is considered the latest development and the most important one in metal joining during the past two decades. At first, FSW gained significant attention as a solid- state joining process of aluminium alloys, but now its application is extended to relatively harder metals and also to plastics. In the FSW technique, a tool with a shoulder and a profiled pin is rotated and slowly plunged into the joint line between two rigidly clamped substrates on a backing plate support. Heat is generated by friction between the rotating tool and the work piece material which leads to softened region near the FSW Tool. Friction stir welding is further enhanced to increase the material properties of a particular material called as “Friction Stir Processing”.

1.9 Friction stir processing:

Use of the friction stir process to modify the microstructure to local region metallurgically. Friction stir processing (FSP) is a method of changing the properties of a metal through intense, localized plastic deformation. This deformation is produced by forcibly inserting a non-consumable tool into the workpiece, and revolving the tool in a stirring motion as it is pushed laterally through the workpiece. When ideally implemented, this process mixes the material without changing the phase (by melting or otherwise) and creates a microstructure with fine, equiaxed grains. This homogeneous grain structure, separated by high-angle boundaries, allows some aluminium alloys to take on superplastic properties. Friction stir processing also enhances the tensile strength and fatigue strength of the metal. In tests with actively cooled magnesium-alloy workpieces, the microhardness was almost tripled in the area of the friction stir processed seam (to 120–130 Vickers hardness).

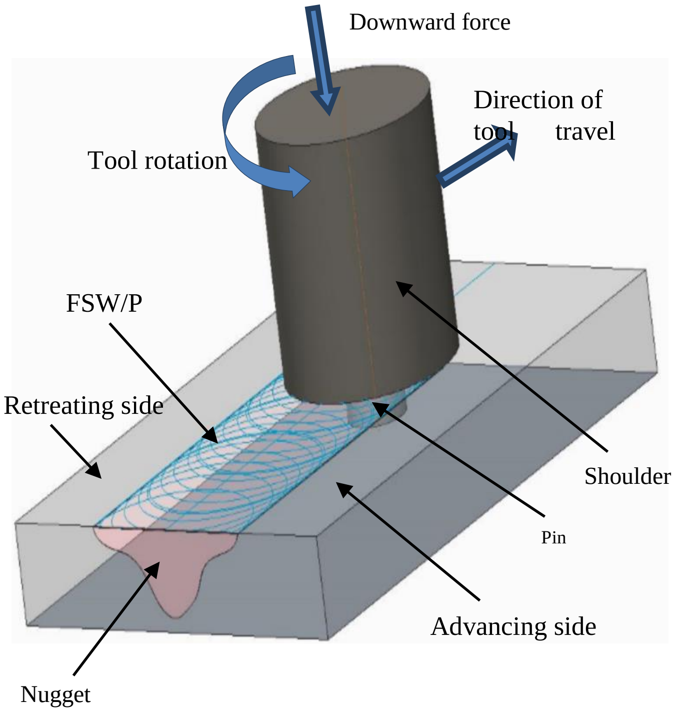


Fig 1: Friction stir processing

In friction stir processing (FSP), a rotating tool is used with a pin and a shoulder to a single piece of material to make specific property enhancement, such as improving the material’s toughness or flexibility, in a specific area in the micro-structure of the material via fine grain of a second material with properties that improve the first. Friction between the tool and workpieces results in localized heating that softens and plasticizes the workpiece. A volume of processed material is produced by movement of materials from the front of the pin to the back of the pin. During this process, the material undergoes intense plastic deformation and this results in significant grain refinement. FSP changes physical properties without changing physical state which helps engineers create things such as “high-strain-rate superplasticity”. The grain refinement occurs on the base material improving properties of the first material, while mixing with the second material. This causes for the base material's properties. This allows for a variety of materials to be altered to be changed for things that may require other difficult to acquire conditions.

1.10 Additive Friction Stir Processing:

Additive Friction Stir Processing can be used for coating, repair, or additive manufacturing of similar or dissimilar materials. The process principle is simple and similar to friction stir welding/processing, with the exception of the use of filler material. Filler materials in the form of solid or powder is fed by hands into the slots and is locked by the pinless tool to avoid scattering during AFSP. The filler materials undergoes severe plastic deformation, dynamic recrystallization, consolidation (if powder), and deposition. AFSP is differentiated from other additive manufacturing technologies because it is a highly scalable, open atmosphere process with a high deposition rate that offers flexibility with material sets and yields a near wrought microstructure on near net shape complex 3D structures. Since additive friction stir is a solid-state process the residual stress formed in the deposited components is much less than the residual stresses developed during casting or other manufacturing processes.

1.11 Advantages:

1. We can change different characteristics of base material e.g. hardness, toughness, abrasiveness, melting point, ductility etc
2. We can control the depth up to which the properties are to be enhanced
3. We can change the microstructure as well as macrostructure of base material
4. We can control the number of properties to be changed

1.12 Disadvantages:

1. Characterisation is difficult
2. Automatic machine used for FSP is bulky and costly
3. After retracting the tool from plate the hole remains in the plate

1.13 Application:

The FSP is used when metals properties want to be improved using other metals for support and improvement of the first. This is promising process for the automotive and aerospace industries where new material will need to be developed to improve resistance to wear, creep, and fatigue. Examples of materials successfully processed using the friction stir technique include AA 2519, AA 5083 and AA 7075 aluminum alloys. Also FSP is used in defence applications such as armours[21].

1.14 Introduction to 7075 Al alloy:

- Composition :

  Zinc :- 5.6 – 6.1%

  Magnesium :- 2.1 – 2.5%

  Copper :- 1.2 – 1.6%

And less than a half percent of silicon, iron, manganese, titanium, chromium, and other metals.

- Properties:
  - Strong with strength comparable to many steels.
  - Good fatigue strength and average machinability.
  - Less resistance to corrosion than most of the al alloys.
  - Relatively high cost limits.

2. LITERATURE REVIEW:

[1] **“Exploring the effects of SiC reinforcement incorporation on mechanical properties of friction stir welded 7075 aluminum alloy: Fatigue life, impact energy, tensile strength.”**

In the current research, the role of SiC nano- particles in improving the mechanical properties of friction stir welded(FSWed) 7075 aluminum alloy is investigated. To this end, friction stir welding (FSW) was conducted at 1250 rpm and 40mm/min. The experiment carried out with and with out in corporating SiC nano-particles along the jointline.Cross-sectional microstructures of the joints were characterized employing optical and scanning electron microscopy (SEM). Results achieved through X-ray diffraction (XRD) confirmed the presence of SiC powders. Moreover, it was discovered that the volume fraction of the reinforcement particles was 20%. Along with an excellent bonding between SiC nano-particles and aluminum matrix, SEM photograph demonstrated a good dispersion of SiC reinforcements. Atomic force microscopy (AFM) results were also in tight agreement with the recent SEM microstructure. Thanks to the presence of SiC nano-particles, tensile strength, percent elongation, fatigue life, and toughness of the joint improved tremendously. The fracture morphologies were in good agreement with corresponding ductility results.

[2] **“Friction stir processing of 7075 Al alloy and subsequent aging treatment.”**

The effect of temperatures and time of post-process aging on the microstructure, mechanical properties and wear behavior of friction stir processed 7075 Al alloy was investigated, using optical microscopy (OM), scanning electron microscopy (SEM), transmission electron microscopy (TEM) and Vickers microhardness tester. The results indicate that homogeneous, equiaxed and fine recrystallized microstructure is obtained with the grain size of 4−5 μm. The hardness value increases up to 30% and 80% in the stir zone and the base material, respectively. Based on the TEM observations, it is concluded that the improved properties following the duplex friction stir−aging process can be attributed to the very fine precipitates. Comparing the single and double aging conditions, the hardness of single aging sample is higher than that of double aging one which can be attributed to the high fraction of very fine spheroidal precipitate in single aging sample. The wear rate is reduced by the aging of Al alloy and a more decrease is achieved after the aging of FSPed sample.

[3]"Friction Stir Processing of AA 7039 Alloy."

In present work, friction stir processing of 5 mm thick plate of Al-Zn-Mg alloy (AA 7039) was carried out using a conical pin and overlap of 50%. Modified surfaces were characterized in respect of macrostructure, microstructure, hardness and tensile properties. It was observed that friction stir processing refined the microstructure of AA 7039 alloy and increased the ductility (%elongation). However, tensile strength and hardness were found to be adversely affected. Hardness has been found to be increased with number of passes during friction stir processing**.**

[4] "Friction Stir Processing of SSM356 Aluminium Alloy"

The aim of this experiment was to improve the mechanical properties of SSM 356 aluminum alloys by friction stir processing, a solid-state technique for microstructural modification using the heat from a friction and stirring. The parameters of friction stir processing for SSM 356 aluminum alloys were studied at three different travelling speeds: 80, 120 and 160 mm/min under three different rotation speeds 1320, 1480 and 1750 rpm. The hardness and tensile strength properties were increased by friction stir processing. The hardness of friction stir processing was 64.55 HV which was higher than the base metal (40.58 HV). The tensile strengths of friction stir processing were increased about 11.8% compared to the base metal. The optimal processing parameter was rotation speed at 1750 rpm with the travelling speed at 160 mm/min. Consequently, the application of the friction stir processing is a very effective method for the mechanical improvement of semi-solid metal aluminum alloys.

[5] "Superplasticity of a Friction Stir Processed 7075-T651 aluminum alloy"

Superplastic forming is a technological process used to produce metallic components with very complex shapes. In the last two decades it has been a topic of major development. In Fine Structure Superplasticity (FSS), the initial grain size exerts a strong influence on the superplastic behavior, affecting the Grain Boundary Sliding (GBS) mechanism. Refining grain size (GS) the parameters of superplastic forming (temperature and strain rate) could be optimized. Thermal stability of grain structure is also an important factor to obtain superplasticity. FSP is technique recently developed used to refine GS. The optimum FSP processing parameters are still under study for different materials. In the present work a 7075-T651 aluminium alloy was friction stir processed in order to improve superplastic behavior. Friction stir processed specimens were tensile tested at temperatures between 350 and 450 °C and initial strain rates between $5x10^{-3}$ and $2.5\ x10^{-2}\ s^{-1}$. A strong influence of both temperature and initial strain rate on the test results was observed. The maximum superplastic elongation was 900% at 400°C and $1x10^{-2}\ s^{-1}$ strain rate. Due to the low temperature and high strain rate used in the tests these results are better to those obtained in previous works and would be associated with the processing conditions and the design of the tool used.

[5] “Enhancement of wear and ballistic resistance of armour grade AA7075 aluminium alloy using friction stir processing”

Industrial applications of aluminium and its alloys are restricted because of their poor tribological properties. Thermal spraying, laser surfacing, electron beam welding are the most widely used techniques to alter the surface morphology of base metal. Preliminary studies reveal that the coating and layering of aluminium alloys with ceramic particles enhance the ballistic resistance. Furthermore, among aluminium alloys, 7075 aluminium alloy exhibits high strength which can be compared to that of steels and has profound applications in the designing of lightweight fortification structures and integrated protection systems. Having limitations such as poor bond integrity, formation of detrimental phases and interfacial reaction between reinforcement and substrate using fusion route to deposit hard particles paves the way to adopt friction stir processing for fabricating surface composites using different sizes of boron carbide particles as reinforcement on armour grade 7075 aluminium alloy as matrix in the present investigation. Wear and ballistic tests were carried out to assess the performance of friction stir processed AA7075 alloy. Significant improvement in wear resistance of friction stir processed surface composites is attributed to the change in wear mechanism from abrasion to adhesion. It has also been observed that the surface metal matrix composites have shown better ballistic resistance compared to the substrate AA7075 alloy. Addition of solid lubricant MoS2 has reduced the depth of penetration of the projectile to half that of base metal AA7075 alloy. For the first time, the friction stir processing technique was successfully used to improve the wear and ballistic resistances of armour grade high strength AA7075 alloy.

[6] "Effect of Friction Stir Processing on (2024-T3) Aluminum Alloy"

In this work, friction stir process (FSP) was used to enhance surface properties of AA2024-T3 alloy. The effect of friction stir shoulder rotation in addition to its pressing effect on surface topography and mechanical properties was studied. Samples were FS processed with a flat pinless cylindrical shoulder of 10mm diameter with a constant rotational and travel speeds 945 rpm and 85mm/min respectively. Results show that processed layer thickness of about 45 μm was produced after FSP. Microscopic examinations (OM and SEM) revealed refining grain size of second phase particles as a result of mixing effect of the tool. XRD results show changes in the height and width of the strengthening phase θ(Al2Cu) peaks, while EDX results show that Al and Cu created at another energy (KeV) compared with those that are not in phase before FSP. The maximum hardness increment is about 40-45% and the maximum value obtained at the surface is 190Hv compared to 130Hv before processing. A little bit increase was recorded in yield and tensile strengths by an amount of 15% and 9% respectively after FSP.

[7] "Effect of minor Sc and Zr addition on the mechanical properties of Friction Stir Processed 2024 Aluminium alloy"

The effect of Friction Stir Processing (FSP) on the mechanical properties of a Sc, Zr modified 2024 aluminium alloy was investigated in the present paper. The room temperature tensile properties of the material were obtained in longitudinal direction respect to the processing one and compared with those of the unstirred material and unmodified alloy. Tensile tests were also performed at higher temperatures and different strain rates in the nugget zone. The superplastic properties of the recrystallized material were evaluated and the differences with the parent material as a function of the strong grain refinement due to the Friction Stir Process were put in evidence. The high temperature behavior of the material was studied, in longitudinal direction, by means of tensile tests in the temperature and strain rate ranges of 450-525oC and 10-1–10-3 s-1 respectively.

[8] “Effect of velocity index on grain size of friction stir processed Al-Zn-Cu-M alloy”

In this study, the effect of velocity index (tool rotation speed /traverse speed) on resulting grain microstructure of friction stir processed high strength Al-Zn-Mg-Cu alloy is reported. The velocity index is a key factor to decide the heat input during the process. Three samples were manufactured at different velocity index. The hardness measurement was performed to understand the hardness distribution in the processed region at different velocity index. The microstructure examination of the stir zone was performed by optical microscope. All the samples exhibited the stir zone with fine equiaxed grain microstructure. It is observed that grain size decreased with decrease in the value of the velocity index.

[9] “Effects of thermal conditions on microstructure in nano composite of Al/Si3N4 produced by friction stir processing”

A novel surface modifying technique has been used for fabrication of surface nano composite layer of Al5754/Si3N4. The effect of traverse and rotational speed on peak temperature was investigated. With the decrease of traverse speed the peak temperature was increased .Further more with increase of rotational speed the peak temperature was increased but in high rotational speed the variation of peak temperature was slight. Also the effect of traverse and rotational speed on stirred zone area was surveyed. The results showed that rotational speed is more effective on stirred zone area than traverse speed. The effect of rotational and traverse speed on grain size was also investigated .It was observed that with increasing the traverse speed to rotational speed ratio the grain size was increased with the exception of some rotational speed such as 1800 rpm. The Si3N4 particles were uniformly distributed in the aluminum matrix. Also the effect of shoulder penetration on fabrication of surface nanocomposite layer was examined .It was observed that under special penetration shoulder, surface nanocomposite layer can be produced. The micro hardness of surface nanocomposites produced under different rotational and traverse speed was also evaluated.

[10] "Microstructure and mechanical properties of 7075 Aluminium alloy by repetition friction stir processing"

7075 aluminum alloy plate with 5mm in thickness was friction stir processed under both single path and repetition path processing for grain refinement. Shape of stir zone (SZ) on macrostructure of single path friction stir processing (FSP) specimen and repetition path specimens that were same direction were asymmetrical structure between advancing side (AS) and retreating side (RS) of the specimen. However repetition path specimen that was reverse direction specimen became symmetrical structure. Microstructures of SZ of both repetition path specimens were shown finer grain structure than that of single path specimen. Grain size of single path specimen had 2.6μm, and repetition path specimen was 2.3μm, these were showed finer than that of base metal such as 28μm. It is tendency that the grain size of SZ on repetition path specimens, same direction path specimen was finer than that of reverse direction path specimen. Harnesses of the SZ of both repetition path specimens were shown lower value than both base metal and single path specimen. Maximum joint efficiency of tensile strength of both repetition specimens showed 85% of base metal.

[11] "High temperature deformation of friction stir processed 7075 aluminium alloy"

The mechanical and microstructural properties of 7075 aluminium alloy resulting from Friction Stir Processing (FSP), into sheets of 7 mm thickness, were analysed in the present study. The sheets were processed perpendicularly to the rolling direction; the tensile mechanical properties were evaluated at room temperature in the transverse and longitudinal directions with respect to the processing one. Tensile tests were also performed at higher temperatures and different strain rates in the nugget zone, in order to analyse the superplastic properties of the recrystallized material and to observe the differences from the parent material as a function of the strong grain refinement due to the Friction Stir Process. The high temperature behaviour of the material was studied, in the parallel direction, by means of tensile tests in the temperature and strain rate ranges of 150–500 8C and 10^{-2} -10^{-4} s^{-1} respectively, electron microscopy (FEGSEM) observations were carried out to investigate more closely the fracturensurfaces of the specimens tested at different temperatures and strain rates.

[12] “Superplastic deformation behaviour of friction stir processed 7075Al alloy”

Commercial 7075Al rolled plates were subjected to friction stir processing (FSP) with different processing parameters, resulting in two fine-grained 7075Al alloys with a grain size of 3.8 and 7.5 μm. Heat treatment at 490 °C for 1 h showed that the fine grain microstructures were stable at high temperatures. Superplastic investigations in the temperature range of 420–530 °C and strain rate range of 1×10^{-3}–1×10^{-1} s^{-1} demonstrated that a decrease in grain size resulted in significantly enhanced superplasticity and a shift to higher optimum strain rate and lower optimum deformation temperature. For the 3.8 μm 7075Al alloy, superplastic elongations of _1250% were obtained at 480 °C in the strain rate range of 3×10^{-3} – 3×10^{-2} s^{-1} , whereas the 7.5 μm 7075Al alloy exhibited a maximum ductility of 1042% at 500 °C and 3×10^{-3} s^{-1}. The analyses of the superplastic data for the two alloys revealed a stress exponent of 2, an inverse grain size dependence of 2, and an activation energy close to that for grain boundary self-diffusion. This indicates that grain boundary sliding is the main deformation mechanism for the FSP 7075Al. This was verified by SEM examinations on the surfaces of deformed specimens.

[13] “Finite element simulation of selective superplastic forming of friction stir processed 7075 Al alloy”

For many superplastically formed components, only some regions undergo superplastic deformation. In these cases, instead of choosing expensive starting sheet material with superplastic properties, a low-cost, conventional material can be chosen and friction stir processing (FSP) can be performed in the selected regions to impart superplastic properties locally. This is called “selective superplastic forming”. In this study, finite element simulation of superplastic forming of a bowl shape component with inhomogeneous properties has been conducted. We chose commercial 7075 Al alloy as the starting material and FSP was used to generate fine grains in some regions. The pressure schedule, the overall forming time and the final thickness distribution in the formed component were calculated. This simulation demonstrates the design possibilities with this new concept.

[14] "Deep cup forming by superplastic punch stretching of friction stir processed 7075 Al alloy"

Multiple overlapping passes of friction stir processing (FSP) were used to cover 80mm wide region for punch stretching of 7075 Al alloy plate. The forming experiments were performed at 723 K. While a maximum depth of 52mm (depth/punch diameter~2.7) could be achieved by punch stretching at a slow strain rate of 10^{-3} s^{-1}, the maximum depth obtained at a higher strain rate of 10^{-2} s^{-1} was 40.4 mm. However, tolerable variations in thickness can be maintained up to a depth of 18.5mm which is nearly equal to the punch diameter. FEM simulation closely predicts the load and thickness variation till the point of initiation of cavities and instabilities.

[15] "Synthesis of multi-walled CNT reinforced aluminium alloy composite via friction stir processing"

Friction stir processing is used to produce an aluminium alloy reinforced with multi-walled carbon nanotubes. Microscopy by SEM and TEM indicates that the nanotubes are embedded into Al-alloy matrix produced in the stir zone, and their multi-walled microstructure survived the thermo-mechanical conditions imposed during processing. Increasing the tool rotation speed from 1500 and 2500rpm and increasing the tool shoulder penetration depth improved homogeneity of nanotubes in the Al-alloy matrix, however a fully uniform distribution could not be achieved when regularly tangled nanotubes were used.

[16] "Multiple passes of friction stir processing for the creation of superplastic 7075 aluminum"

A staggered pass sample of friction stir processed (FSP) 7075 aluminum was created to make samples with one through four passes of FSP under identical conditions. The tensile testing temperatures ranged from 673 to 763K with initial strain rates ranging from 1×10^{-3} to 1×10^{-1} s^{-1}. Materials processed by single as well as multiple passes exhibited superplasticity across various testing temperatures and strain rates while the as received materials exhibited elongations below 200%. This study demonstrated the effectiveness of four consecutive FSP passes in creating large areas of superplastic material. However, the largest elongations were observed for the single pass material.

[17] "Friction Stir Welding/Processing Tool Materials and Selection"

The tool material selection depends on the tool material operational characteristics such as operational temperature, wear resistance and fracture toughness which therefore determine the type of materials which can be joined. In this research, several tool materials have been analysed and the materials which they could be used to join have also been outlined. Soft materials can be easily welded using tool steels while harder materials need harder tool materials such as carbide based materials and polycrystalline cubic boron nitride (PCBN).

[18] "Review of tools for friction stir welding and processing"

Friction stir welding (FSW) is a novel green manufacturing technique due to its energy efficiency and environmental friendliness. This solid state joining process involves a rotating tool consisting of a shoulder and/or a probe. The shoulder applies a downward pressure to the workpiece surface, constrains the plasticised material around the probe, generates heat hrough the friction and causes plastic deformation in a relatively thin layer under the bottom surface of the shoulder. The rotating probe mainly drags along, plasticises, and mixes the adjacent material in the stir zone, creating a joint without fusion. Friction stir processing (FSP), a variant of FSW, has been developed to manufacture composites, locally eliminate casting defects, refine microstructure and/or improve the associated mechanical and physical properties including strength, ductility, fatigue, creep, formability and corrosion resistance. However, major challenges such as tool design and wear currently limit the use of FSW/P for manufacturing applications, particularly for high melting temperature or high strength alloys. In this review, the FSW/P tools are briefly summarized in terms of the tool types, shapes, dimensions, materials and wear behaviors.

[19] "Review: friction stir welding tools"

Friction stir welding (FSW) is a widely used solid state joining process for soft materials such as aluminium alloys because it avoids many of the common problems of fusion welding. Commercial feasibility of the FSW process for harder alloys such as steels and titanium alloys awaits the development of cost effective and durable tools which lead to structurally sound welds consistently. Material selection and design profoundly affect the performance of tools, weld quality and cost. Here we review and critically examine several important aspects of FSW tools such as tool material selection, geometry and load bearing ability, mechanisms of tool degradation and process economics.

[20] "Effect of small tool pin profiles on microstructures and mechanical properties of 6061 aluminum alloy by friction stir welding"

The effect of small tool pin profiles on the microstructures and mechanical properties of 6061 aluminum alloy joints using friction stir welding (FSW) technique was investigated. Three different tool pin profiles: threaded tapered cylindrical, triangular and square were used to produce the joints. The results indicate that the weld joints are notably affected by joining with different tool pin profiles. The triangular tool pin profile produces the best metallurgical and mechanical weld properties compared with other tool pin profiles. Besides, the lowest tensile strength and microhardness are obtained for the joint friction stir welded with square tool pin profile. It is observed that the smaller tool pin profile and shoulder diameter lead to narrow region of heat affected zone (HAZ) and a desired level of softening. The fracture surface examination shows that the joints are also affected when welding with different types of tool pin profiles. The fracture surface shows that the triangular specimen fails with a ductile fracture mode during the tensile test, while the brittle fracture modes are observed in the joints fabricated with other tool pin profiles.

[21] Fabrication of Mg-ZrO2 surface layer composites by friction stir processing

Observed enhancement in mechanical properties of the produced composite was attributed to refinement of the microstructure. This was achieved by fine dispersion of hard particles of ZrO2 and their pinning effect on the grain boundaries. The measured amounts of SZ microhardnesses in the fabricated composite were compared to the results calculated by a Hall-Petch type equation already developed to obtain hardness versus grain size. A soft and ductile Magnesium foil was also inserted in the workpiece in order to study the strain rate generated by the pin during FSP. The effect of nano-particles dispersion on the material flow around the pin was also investigated using another Mg foil inserted in the workpiece. Adding the ceramic particles enhanced the applied severe plastic deformation and raised the strain rate of the materials during FSP.

[22] Fabrication of Al7075/TiB2 Surface Composite via Friction Stir Processing.

In this work friction stir processing was utilized to successfully disperse and embed TiB2 particles with global size of 2.62 μm in Al 7075. The effects of rotational and traverse speeds with two FSP passes on particle distribution and microstructures were studied. Microstructure observations were carried out by employing optical microscopy and scanning electron microscopy (SEM) of the modified surface. The results showed that increasing the rotational speed caused a more uniform distribution of TiB2 Particles. Microhardness of the cross section and tensile test result were also evaluated. The microhardness values of produced composite surface raise with increasing the rotational and traverse speed and improved almost 3 times as compared with base aluminium. Tensile test result shows rising in yield strength by more than two times of base metal.

[23] Friction stir processing of a Zr-modified 2014 aluminium alloy

The mechanical and microstructural properties of a Zr-modified 2014 aluminium alloy resulting from friction stir processing were analyzed. The sheets were processed parallel to the extrusion direction, the tensile mechanical properties were evaluated at room temperature in transverse and longitudinal direction respect to the processing one. Tensile tests were also performed at higher temperatures and different strain rates in the nugget zone, in order to analyze the superplastic properties of the recrystallized material and to observe the differences with the parent materials as a function of the strong grain refinement due to the friction stir process. The high temperature behavior of the material was studied, in the parallel direction, by means of tensile tests in the temperature and strain rate ranges of 400–500 ◦C and 10−2 to 10−4 s−1, respectively. Scanning electron microscopy (field-emission gun) examinations were also carried out to investigate more closely the fracture surfaces of the specimens tested at different temperatures and strain rates.

The dynamic recrystallized structure of the material was observed by employing optical and electron microscopy. The room temperature and high temperature tensile properties of the heavily refined structure resulted optimal for superplastic deformation thanks to very high levels of strain to fracture and strain-rate sensitivity exhibited at high strain rate levels (10−2 s−1).

[24]Fabrication of 5052Al/Al2O3 nanoceramic particle reinforced composite Via friction stir processing route

In this research, microstructure and mechanical properties of 5052Al/Al2O3 surface composite fabricated by friction stir processing (FSP) and effect of different FSP pass on these properties were investigated. Two series of samples with and without powder were friction stir processed by one to four passes. Tensile test was used to evaluate mechanical properties of the composites and FSP zones. Also, microstructural observations were carried out using optical and scanning electron microscopes. Results showed that grain size of the stir zone decreased with increasing of FSP pass and the composite fabricated by four passes had submicron mean grain size. Also, increase in the FSP pass caused uniform distribution of Al2O3 particles in the matrix and fabrication of nano-composite after four passes with mean cluster size of 70 nm. Tensile test results indicated that tensile and yield strengths were higher and elongation was lower for composites fabricated by three and four passes in comparison to the friction stir processed materials produced without powder in the similar conditions and all FSP samples had higher elongation than base metal. In the best conditions, tensile strength and elongation of base material improved to 118% and 165% in composite fabricated by four passes respectively.

[25] Surface modification of aluminium by friction stir processing

In this study, SiC particles were incorporated by using Friction Stir Processing (FSP), into the commercially pure aluminium to form particulate surface layers. Samples were subjected to the various tool rotating and traverse rates with and without SiC powders. Microstructural observations were carried out by employing optical microscopy of the modified surfaces. Mechanical properties like hardness and plate bending were also evaluated. The results showed that increasing rotating and traverse rate caused a more uniform distribution of SiC particles. The hardness of produced composite surfaces was improved by three times as compared to that of base aluminium. Bending strength of the produced metal matrix composite was significantly higher than processed plain specimen and untreated base metal.

[26] Improving the tribological characteristics of aluminium 6061 alloy by surface compositing with sub-micro-size ceramic particles via friction stir processing

This study presents a solid state surface engineering technique for forming a composite surface layer on aluminium to improve surface hardness and wear resistance without sacrificing the ductility and conductivity of the bulk. Friction stir processing (FSP) was used to stir and mix sub-micro-size Al_2O_3 and SiC particles into the surface of an aluminium 6061-T651 alloy plate to form a composite layer of up to 3 mm thick. The concentration of the hard phase was in the range of 20–30 vol. %. Compared with a nonprocessed aluminium surface, the FSP-formed composite surface exhibited substantial friction and wear reductions by 40% and 90%, respectively, when rubbed against a bearing steel. Post-FSP heat treatment afforded further enhancement of the wear resistance. Transmission electron microscopy revealed high matrix dislocation density in the composite surface that is believed to be largely responsible for such significant properties improvements.

[27] An experimental study on multi-pass friction stir processing of Al/TiN composite: some microstructural, mechanical, and wear characteristics

TiN is an exceptionally hard and a wear-resistant ceramic. In the present work, the effect of mixing TiN particulates into the Al7075-T651 alloy was studied by employing a novel material fabrication technique called friction stir processing (FSP). The FSP was carried out using three different tool geometries (namely square, triangular, and threaded taper) with an objective to fabricate the Al/TiN composite with an appropriate set of mechanical and wear properties. A number of microstructural, mechanical, and wear tests were carried out in order to characterize the composite. In comparison to the parent metal, each of the composite specimens showed improved wear and friction performance. However, the improvement in the hardness was realized only with the threaded tool and that in the tensile strength was observed with the square tool, thus revealing a tool-property relationship in FSP. Contrarily, the ductility of all of the composite specimens was lower relative to that of the parent metal. A suitable trade off among various characteristics was realized when FSP was performed using the square tool. The microscopic and energy dispersive spectroscopy (EDS) analyses showed that the dominant wear mechanism in the composite was adhesion. This study is the first report on the FSPed Al/TiN composite.

[28] Ballistic behaviour of boron carbide reinforced AA7075 aluminium alloy using friction stir processing e An experimental study and analytical approach

High strength-to-weight ratio of non-ferrous alloys, such as aluminium, magnesium and titanium alloys, are considered to be possible replacement of widely accepted steels in transportation and automobile sectors. Among these alloys, magnesium is self-explosive and titanium is costlier, and aluminium is most likely to replace steels. Application of aluminium or its alloys is also thought of as an appropriate replacement in defence field, especially to enhance the easiness in mobility of combat vehicles while maintaining the same standard as that of conventional armour grade steels. Hence most of the investigations have been confined to aluminium or its alloys as base material and open an era of developing the newer composite materials to address the major limitation, i.e. tribological properties. The surface composites can be fabricated by incorporating the ceramic carbides like silicon carbide, carbides of transition metals and oxides of aluminium using surface modification techniques, such as high energy laser melt treatment, high energy electron beam irradiation and thermal spray process which are based on fusion route. These techniques yield the fusion related problems, such as interfacial reaction, pin holes, shrinkage cavities or voids and other casting related defects, and pave the way to need of an efficient technique which must be based on solid state. Recently developed friction stir processing technique was used in the present investigation for surface modification of AA7075 aluminium alloy, which is an alternative to steels. In the present investigation, 160 mm sized boron carbide powder was procured and was reduced to 60 mm and 30 mm using high energy ball mill. Subsequently these powders were used to fabricate the surface composites using friction stir processing.

Ballistic performance testing as per the military standard (JIS.0108.01) was carried out. In the present work, an analytical method of predicting the ballistic behaviour of surface composites was developed. This method was based on energy balance, i.e., the initial energy of impact is same as that of energy absorbed by multi layers. An attempt also has been made to validate the analytical results with the experimental findings. Variation between the analytical and experimental results may be accounted due to the assumptions considering such as isotropic behavior of target and shearing area of contact as cylindrical instead of conical interface. As the analytical model yields the ballistic performance in the closer proximity of experimentally obtained, it can be considered to be an approximation to evaluate the ballistic performance of targets.

[28] Development of quartz particulate reinforced AA6063 aluminium matrix composites via friction stir processing

The present work focuses on the development of AMCs reinforced with quartz ($SiO2$) particles using FSP. Grooves with various dimensions were machined on AA6063 plates and compacted with quartz particles. A single pass FSP was carried out using a combination of optimized process parameters. The volume fraction of quartz particles in the AMCs was varied from 0 to 18 vol. % in steps of 6 vol. %. The developed

AA6063/Quartz AMCs were characterized using optical, scanning and transmission electron microscopy. The quartz particles were distributed uniformly in the aluminum matrix irrespective of the location within the stir zone. The grains of the AA6063 were extensively refined by the combination of thermo mechanical effect of FSP and the pinning effect of quartz particles. The dispersion of the quartz particles improved the microhardness and wear resistance of the AMCs. The role of quartz particles on the worn surface and wear debris is reported.

[29] Effect of friction stir processing with B4C particles on the microstructure and mechanical properties of 6061 aluminium alloy

In this paper, friction stir processing (FSP) with B4C particles (B4Cp) is used to improve the surface modification of 6061 aluminium alloy. Optical microscopy, scanning election microscopy, and energy-dispersive X-ray analysis have been performed to investigate the microstructure and the distribution of B4Cp. Wear resistance and Microhardness were evaluated in detail. It is observed that the increasing number of FSP passes causes a more uniform distribution of B4Cp. The homogeneous distribution of B4Cp was observed in the weld zone, which significantly improved the wear resistance and microhardness of the surface composite layer as compared to those of the as received Al alloy.

[30] Effect of tool pin profile on distribution of reinforcement particles during friction stir processing of B4C/aluminium composites

Boron carbide /aluminium composites have been produced on an aluminium–silicon cast alloy using friction stir processing. Effect of pin profile on the distribution of boron carbide in the stir zone of the friction stir processed specimens was investigated experimentally and numerically. The material flow generated by the threaded and circular tool pin profiles, being the main reason for the distribution of particles in the metal matrix, was numerically modelled using a thermo mechanically coupled three-dimensional finite element model. Numerical and experimental results show that threaded pin profile produces a more uniform distribution of B4Cp than other pin profiles. Hardness tests were performed in order to investigate mechanical properties of the composites. Wear resistance of the composite was evaluated and obtained results showed that the hardness and wear resistance of the composite significantly improved.

[31] Effects of friction stir processing on the microstructure and superplasticity of insitunano-ZrB2/2024Al composite

In this study, in situ nano-ZrB2/2024Al composites fabricated from 2024Al–K2ZrF6–KBF4 system were processed by friction stir processing (FSP) to achieve superplasticity of the composites. And the effects of particle contents (1wt%,3wt%,5wt%), matrix grain size (micron or sub- micron), strain rates and deformation temperatures (400K,480K,600K,700K,750K) on the superplasticity of the composites were investigated. After the friction stir processing, the coarse grains of the cast composites with matrix grain size of about 80–100 μm and nano-ZrB2 reinforcement size of 30–100 nm were crushed into small grains about 1 μm in size, and the uniformity of the nano-ZrB2 reinforcements was also improved. And under the same superplastic tensile testing condition at the temperature of 750K and strain, the FSP nano 3 wt. % ZrB2/2024Al composite exhibited a superplastic longation of 292.5%, while the elongation of the corresponding cast composite was only less than 100%. Meanwhile, the m values of the FSP composites were always higher than the cast composites, especially the FSP composites with 3 wt. % particles has the m value of 0.5321 i.e., the FSP composites should had better superplastic properties than cast ones. Furthermore, the FSP composites had higher apparent deformation activation energy (Q) than that of the lattice diffusion of pure aluminium, indicating that the deformation mechanisms of the FSP composites should be grain boundary sliding mechanisms.

[32] Fatigue fracture of friction-stir processed Al–Al3Ti–MgO hybrid nanocomposites.

This paper presents experimental results on the fatigue properties of Al-matrix nanocomposites prepared by the friction stir processing (FSP) technique. An Al–Mg alloy (AA5052) with different amounts (_2 and 3.5 vol%) of pre-placed TiO2 nanoparticles were FSPed up to 6 passes to attain homogenous dispersion of nano-metric inclusions. Microstructural studies by electron microscopic and electron back scattering diffraction (EBSD) techniques showed that nano-metric Al3Ti (50 nm), TiO2 (30 nm), and MgO (50 nm) particles were distributed throughout a fine-grained Al matrix (<2 lm). Consequently, a significant improvement in the tensile strength and hardness was attained. Uniaxial stress-controlled tension– tension fatigue testing (R = 0.1) were utilized to evaluate the fatigue behavior of the prepared nanocomposites. The results were compared with the un-processed (annealed) and FSPed alloy without pre-placing TiO2 particles. It was found that FSP of the aluminium alloy increased the fatigue strength (at 107 cycles) for about 28% and 32% compared with the annealed specimen when the concentration of the reinforcing particles was 2 and 3.5 vol%, respectively. Fractographic analysis determined a ductile fracture behavior with deep-equiaxed dimples for the annealed and FSPed alloy. The facture surface of the nanocomposites revealed a combined ductile–brittle fracture mode with finer dimples. The mechanism of the fatigue fracture and the role of nano-metric inclusions were elaborated.

[33] Effect of Friction Stir Processing on the Microstructure and Hardness of an Aluminium–Zinc–Magnesium–Copper Alloy with Nickel Additives

The main object of this study is to investigate the effect of friction stir processing (FSP) on the microstructure and hardness of Al–Zn–Mg–Cu alloys that were produced via casting with the addition of 5 wt. % nickel. Furthermore, a single pass FSP with a rotational speed of 1500 rpm and a traveling speed of 40 mm/min was performed on the alloys. The FSP treated cast alloys were homogenized, aged at 120°C for 24 h, retrogressed at 180°C for 30 min, and then reaged at 120°C for 24 h. Microstructural evaluations via optical microscopy and scanning electron microscopy, as well as with energy dispersive X ray spectroscopy were conducted. In addition, X ray diffraction analysis was performed to detect the intermetallic and phases of the Al–Zn–Mg–Cu–Ni alloys. Before FSP, the microstructural observations indicated the presence of coarse Ni dispersed particles with a precipitate phase within the matrix. After FSP treatment, the grain refinement led to the uniform space distribution of Ni dispersed particles in the stir zone. The Vickers hardness values for the Al–Zn–Mg–Cu–Ni alloy increased after age tempering at T6 and retrogression and reaging (RRA) treatment because of the increased precipitation and particles dispersity. The hardness of the Al–Zn– Mg–Cu–Ni alloy was enhanced after FSP and a series of heat treatments, especially the RRA process, because of the stirring action of the FSP tool, the grain refinement, the appearance of additional precipitates, and the refinement of dispersed Ni particles.

[34] Interfacial microstructure and properties of aluminium–magnesium AZ31B multi-pass friction stir processed composite plate

A composite plate of 1060Al and AZ31B was fabricated by multi-pass friction stir processing (MP-FSP). The microstructure and properties of the interface were investigated. Intermetallic compounds (IMCs) containing $Al_{12}Mg_{17}$ (γ) and Al_3Mg_2 (β) were formed in the conversion zone (CZ). The morphology of the microstructure in the CZ changed significantly among different travel speeds. Transmission electron microscopy (TEM) of the CZ revealed that the presence of $Al_{12}Mg_{17}$ (γ) grains in the CZ and the rectangular shaped Al_3Mg_2 phase with the dimension about 830 nm length and 500 nm width was detected. Shear tensile test results indicated that the failure load can reach its maximum by decreasing the travel speeds to 4 mm/min. Microhardness measurements indicated that mechanical properties were affected by FSP parameters and mainly depended on the formation of IMCs in the CZ. Fracture morphology studies indicated that the presence of IMCs in the CZ controlled the failure mode. In addition, corrosion test results indicated that the corrosion resistance of the 1060Al/AZ31B clad plate was higher than the multi-pass friction stir processed AZ31B and AZ31B parent material.

[35] Microstructure and Impression Creep Behavior of Al Based Surface Composite Produced by Friction Stir Processing

Al–Fe surface composites were prepared through friction stir processing route by using commercial pure aluminium sheet and iron powder. Friction stir processing was done with a tool made up of high speed steel having a 3 mm pin at the tip. Microstructural features of the friction stir nuggets were characterized by using X-ray diffractometry, scanning electron microscopy, energy dispersive spectroscopy and transmission electron microscopy. Creep behaviour of the friction stir zone was studied using impression creep techniques. Impression creep experiments were done on substrate aluminium and friction stir region. The results show that the surface of Al substrate is converted into a composite, consisting of Al, Fe powders and iron aluminides. The aluminium grain size is drastically reduced, with a large fraction of crystallites having size in the range of 70 nm. Fe particle size was reduced drastically resulting in interparticle spacing in the range of 500 nm. Dislocation density was drastically increased. Impression creep experiments indicated that friction stirred region shows marginally lower activation energy compared to the base metal. This is attributed to the metastability in the structure in the form of extremely fine grain size and high dislocation density. Because of the combined effect, creep in stir zone takes place with a smaller activation energy compared to creep in base aluminium.

[36] Strategy for severe friction stir processing to obtain acute grain refinement of an Al–Zn–Mg–Cu alloy in three initial precipitation states

An Al–Zn–Mg–Cu, Al 7075, alloy was subjected to friction stir processing (FSP) using several processing conditions, two different backing anvils and three initial precipitation states in order to reach the maximum feasible processing severity to produce ultrafine grain sizes. Microstructures formed by fine, equiaxed and highly misoriented grains were obtained. Grain sizes were situated in the range of 200–1000 nm, making FSP competitive with other severe plastic deformation techniques. No influence of the initial precipitation state in the processed grain size was perceived. In fact, the processing conditions and the cooling rate determine the observed grain size. It was found that the selection of the appropriate processing conditions delivered an ultrafine grain size, thus allowing suitable microstructural control.

[37] The influence of multi-pass friction stir processing on the microstructural and mechanical properties of Aluminium Alloy 6082

Samples with one through three passes with 100% overlap were created using friction stir processing (FSP) in order to locally modify the microstructural and mechanical properties of 6082-T6 Aluminum Alloy. A constant rotational speed and three different traverse speeds were used for processing. In this article, the microstructural properties in terms of grain structure and second phase particles distribution, and also the mechanical properties in terms of hardness and tensile strength of the processed zone were addressed with respect to the number of passes and traverse speeds. The parameter combination which resulted in highest ultimate tensile strength was further compared with additional two rotation speeds. FSP caused dynamic recrystallization of the stir zone leading to equiaxed grains with high angle grain boundaries which increased with increasing the number of passes. The accumulated heat accompanying multiple passes resulted in increase in the grain size, dissolution of precipitates and fragmentation of second phase particles. Increasing the traverse speed on the other hand did not affect the grain size, yet reduced the particles size as well as increased the particle area fraction. Hardness and tensile test results of the stir zone were in good agreement where increasing the number of passes caused softening and reduction of the ultimate tensile strength, whereas, increasing the traverse speed increased the strength and hardness. Increasing the tool rotational speed did not have a significant influence on particle mean diameter, ultimate tensile strength and hardness values of the stir zone, whereas, it caused an increase in mean grain size as well as particle area fraction.

[38] Modification of electrical conductivity by friction stir processing of aluminium alloys

A wide range of solid-state manufacturing technologies for joining and modification of material original properties are assuming increasing importance in industrial applications. Among these, friction stir-based technologies are the most significant, namely, friction stir processing (FSP) and friction stir surfacing. The electrical conductivity is a significant property undergoing modification, but this property has not been characterized and fully exploited from the technological point of view. The present work aims to study the electrical conductivity behaviour in FSP of aluminium alloys in order to identify the major factors governing this property. FSP was applied on AA1100, AA6061-T6, and AA5083-H111 alloys with different parameters. Electrical conductivity profiles were measured at different depths and compared with hardness profiles and microstructures. It was found that solid-state friction stir processing of aluminium alloys lead to electrical conductivity changes of about 4%IACS (International Annealed Copper Standard). These changes are more intense in heat-treatable alloys than in work-hardenable ones. Higher rotating versus travel speed ratios (Ω/V) induce higher variations in the electrical conductivity. In FSP, the factors governing the electrical conductivity variations are mostly the grain size and the presence of precipitates. It was shown that, for some FSP applications, electrical conductivity may be a process characterization method more precise and meaningful than hardness to assess local material condition.

[39] Enhancing strength, ductility and machinability of a Al–Si cast alloy by friction stir processing

Cast Al–Si alloys are used for automotive applications. Friction stir processing (FSP) is being used in recent years to improve the performance of these alloys. Secondary machining operations are highly essential on friction stir processed materials to improve the surface finish. However, machinability of friction stir processed cast alloys has rarely been reported. The influence of friction stir processing on microstructure, mechanical properties and machinability of a cast Al–Si alloy was studied in the present work. The main objective is to correlate the metallurgical and mechanical characteristics to the machinability of the friction stir processed material. The age hardening response of as received cast alloy and friction stir processed alloy on machinability and mechanical behaviour was also investigated. The strength, ductility and machinability of friction stir processed alloy before and after age hardening treatment were observed to be higher than that of as received cast alloy. The significant improvement in properties of friction stir processed alloy is due to elimination of porosity, formation of fine recrystallized grain structure, homogenization of silicon particles and dissolution of iron rich intermetallics.

[40] The strengthening mechanism of spray forming Al-Zn-Mg-Cu alloy by underwater friction stir welding

Spray forming Al-Zn-Mg-Cu alloy has been welded successfully by underwater Friction Stir Welding (underwater FSW). The joint is defect-free with tensile strength of 406.06MPa and improved elongation (1.96%).Microstructure of underwater joint has been improved in which the hard-etched area is eliminated compared with traditional joint. The microstructure of joints was observed by OM and SEM. EDS, DSC, XRD and TEM were applied to do further study on the evolution of strengthening phases. The results show that water cooling method has improved the thermal cycle of welding. The microstructure of joint and the strengthening mechanism of underwater joint had a close relationship with the effect of water cooling method. The system analysis of underwater FSW process has been illustrated. Water cooling method creates rapid cooling process to introduce GPII zone and reserve a large amount of needle-like semi-coherent structure $MgZn_2$. The strength of joint has been enhanced by coherency strengthening.

3. EXPERIMENTAL DETAILS:-

3.1 Selection of Tool Material and Design:

Tool:

The tool has a crucial part to creation of the final product. The tool consists of two main functions:

1. Localized heating
2. Material flow

The tool at its simplest form consist of a shoulder, a small cylinder with a diameter of 12 mm, and a pin of 3mm. The tool itself has been modified to reduce displaced volume of the metals as they merged together.

Tool shoulder: The region of tool in contact with the workpiece surface. To enhance the material flow, tool shoulder can have negative or positive scrolls. A negative scroll is a depression in the shoulder surface and the workpiece material fills this. A positive scroll is a protrusion on the shoulder surface. Both types of scrolls conceptually enhance the material flow inward. The other design choice for the shoulder is concave or convex. Concave shoulders were designed to hold the workpiece material in a cup shape. The convex shoulders are relatively new and they require negative scroll spiral (or groves) to contain the material. The advantage of convex shoulder lies in its ability to tolerate minor variability in workpiece thickness.

Tool pin: also referred to as probe in some literature, the pin of the tool is inserted in the workpiece and it influences the horizontal material flow from front to back, as well as vertical material flow from top to bottom. The most common pin profiles are cylindrical or conical. The pins can be threaded or have step spiral design. In addition, the flow can be influenced by putting flats or flutes. The overall possibilities of variations can be extremely large.

Advancing side: the tool pin surface rotation direction and the tool traverse direction have the same vectorial sense. Because of the tool's forward movement, the material wants to flow back, but the pin surface rotation opposes that flow on this side of the tool.

Retreating side: the tool pin surface rotation direction and the tool traverse direction have the opposite vectorial sense. The material flow is easier on this side of the tool pin as the pin surface helps the material flow backward.

Leading edge: the front side of the tool. The tool shoulder meets the cold workpiece material in this region. The tool shoulder sweeps the top layer sideways toward the retreating side and this can have implication of the overall material flow and weld nugget appearance.

Trailing edge: the back side of the tool. The trailing part keeps pumping heat in the workpiece after pin has crossed the region. This influences the microstructural evolution after the pin induced deformation.

Tool rotation rate: the rate at which the tool rotates. This has major contribution to the heat input and material flow.

Tool traverse speed: the travel speed of the tool. This impacts the overall thermal cycle.

Tilt angle: the angle between the plane normal of workpiece and the spindle shaft. Typically an angle between 0 and 3_ is selected.

Work angle: it is an angle between the spindle shaft and the workpiece normal in the z–y plane. This is rarely used in gantry style machine, but can be useful for robotic machine due to the machine stiffness issues.

Plunge rate: the rate at which the tool is inserted in the workpiece. It controls therate of heat build-up and force during the start of the process.

Plunge depth: the programmed depth of the pin bottom from the top surface of rate of heat build-up and force during the start of the process.

Plunge depth: the programmed depth of the pin bottom from the top surface of workpiece. For position-controlled runs, this is a critical number.

Plunge force: the vertical force on the tool when shoulder meets the top surface of workpiece. For force-controlled runs, this is the target force.

Z-axis: the workpiece normal is referred to as the z-axis and this is also the direction of plunge force. A convenient way to look at the forces is from tool’s perspective. Vertical up direction is compressive force on the tool.

X-axis: the travel direction is referred to as the x-axis. The tool pin experiences compressive force from front to back.

Y-axis: the direction normal to the travel direction is the plane parallel to the top surface. The tool pin experiences compressive force from retreating side to advancing side because of the imbalance of material flow around the pin. Unaffected material or parent metal: This is material remote from the weld, which has not been deformed, and which although it may have experienced a thermal cycle from the weld is not affected by the heat in terms of microstructure or mechanical properties.

Required properties of tool material are:

1. Resistance to wear
2. Good strength, dimensional stability and creep resistance at ambient and elevated temperature
3. Good thermal fatigue strength to resist repeated thermal cycles
4. Good fracture toughness.

Different types of tool materials used in FSP are as follow:

1. **Tool steel**
2. **WC-Co**
3. Ni alloys
4. Composite materials
5. W alloys
6. PCBN

We have selected Tool Steel and WC-Co as per the requirement of the project.

- Tool steel (H13) has good machinability and thermal fatigue and can be used to weld both similar and dissimilar welds as lap and butt joints.
- H13 has good shock and abrasion resistance and high toughness.
- WC-Co has a superior wear resistance at ambient temperature.

3.2 Tool Design:

- Tools are classified as :

1. Fixed
2. Adjustable
3. Self-reacting(bobbin type)

As per the requirement of the project Fixed Tool is seem appropriate and has been selected for the experimentation.

- Tool has following parts:

1. Probe or Pin
2. Shoulder
3. Shank

Different types of tool shapes are as follows:-

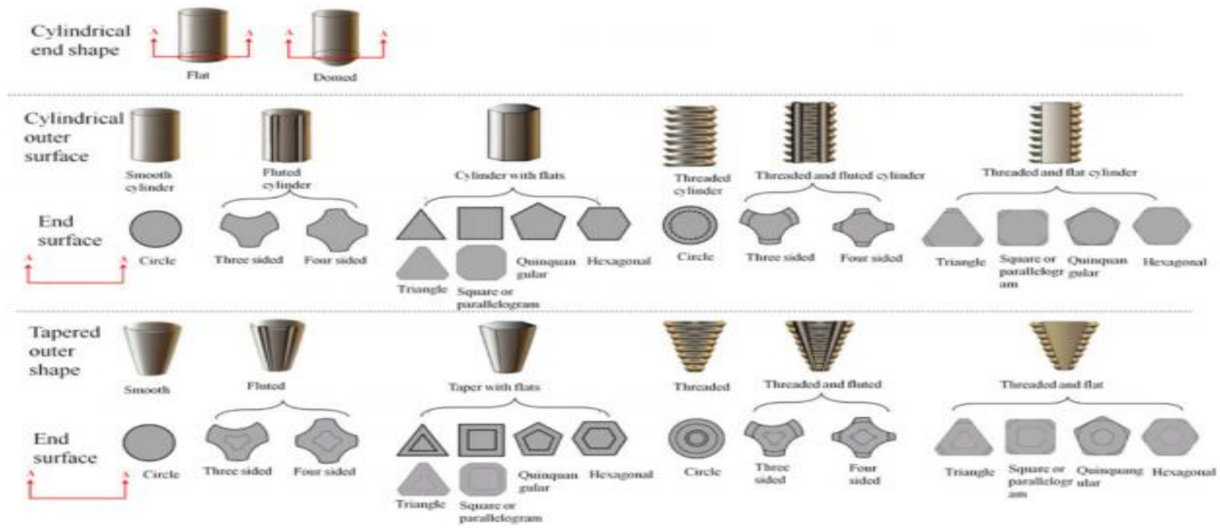


Fig 2**:** Types of Tool Probes

As per the requirement of the project Square Tool Profile and Tapered Cylindrical Tool with Thread gives the best possible results and are selected for the experimentation.

1. Tapered Cylindrical Tool with Thread:-

In this tool the thread provided gives good friction as well as good superplastic flow. The 3D view of the tool is being shown in fig. 3. The stress analysis of the same is being done and is as shown in fig.4

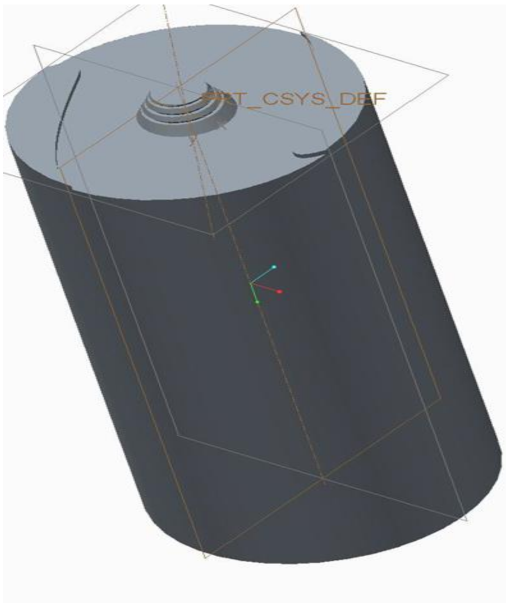


Fig 3: 3D Model of Tapered Cylindrical Tool with Thread

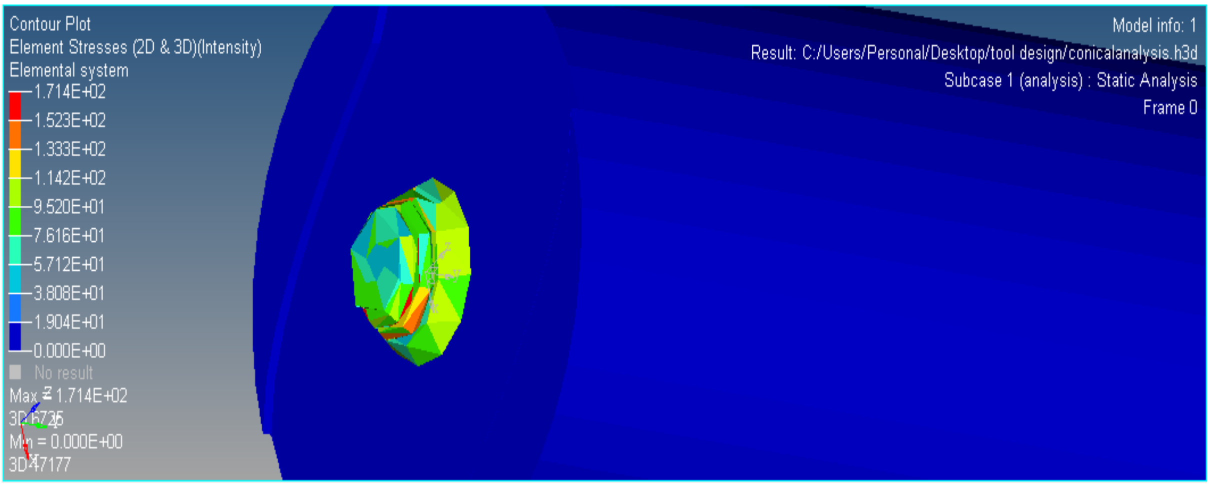


Fig 4: Conical Tool Profile Stress Analysis

2. Square Tool Profile:-

Due to increased surface area and due to the edge effect the superplastic flow is better than other tools. Concave shoulder helps in relocating the plastic flow of material and restricting material extrusion from sides. The 3D model of tool is as shown in fig. 5 and stress analysis is shown in fig. 6

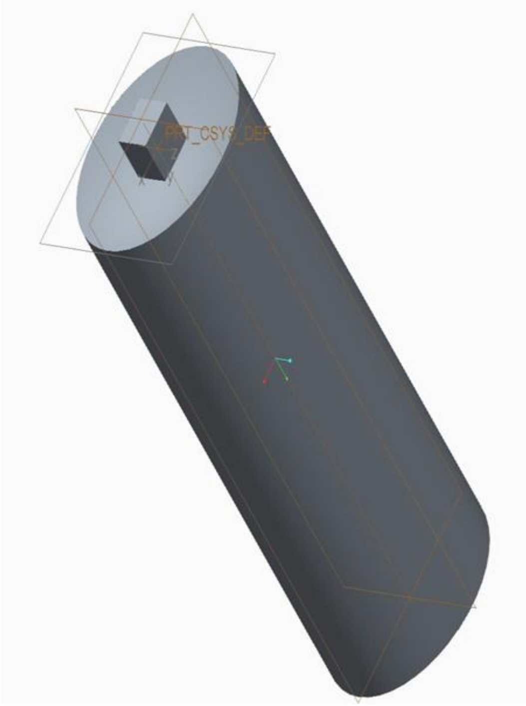


Fig5: 3D Model of Square Tool

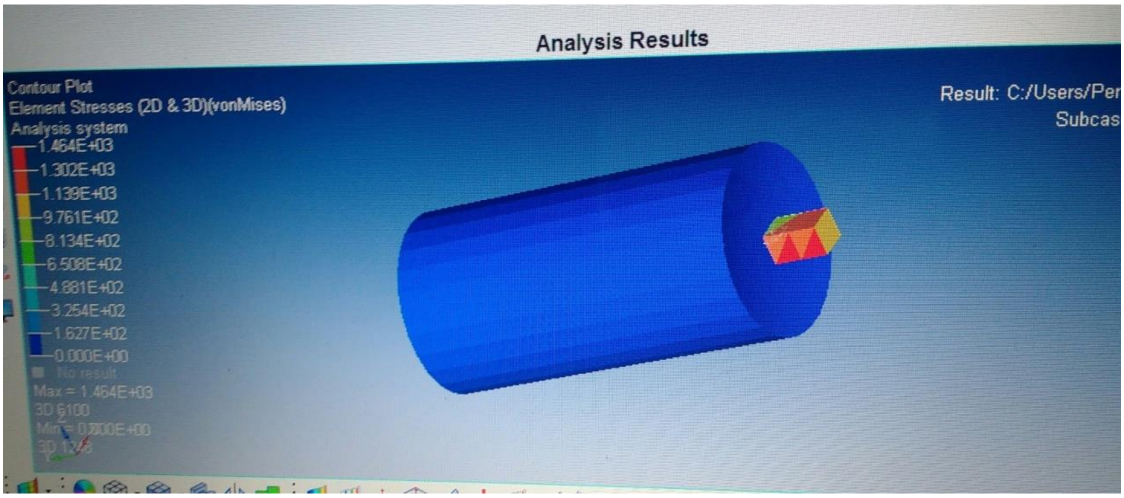


Fig6: Square Tool Profile Stress Analysis

The manufactured tools are shown in the fig 7.

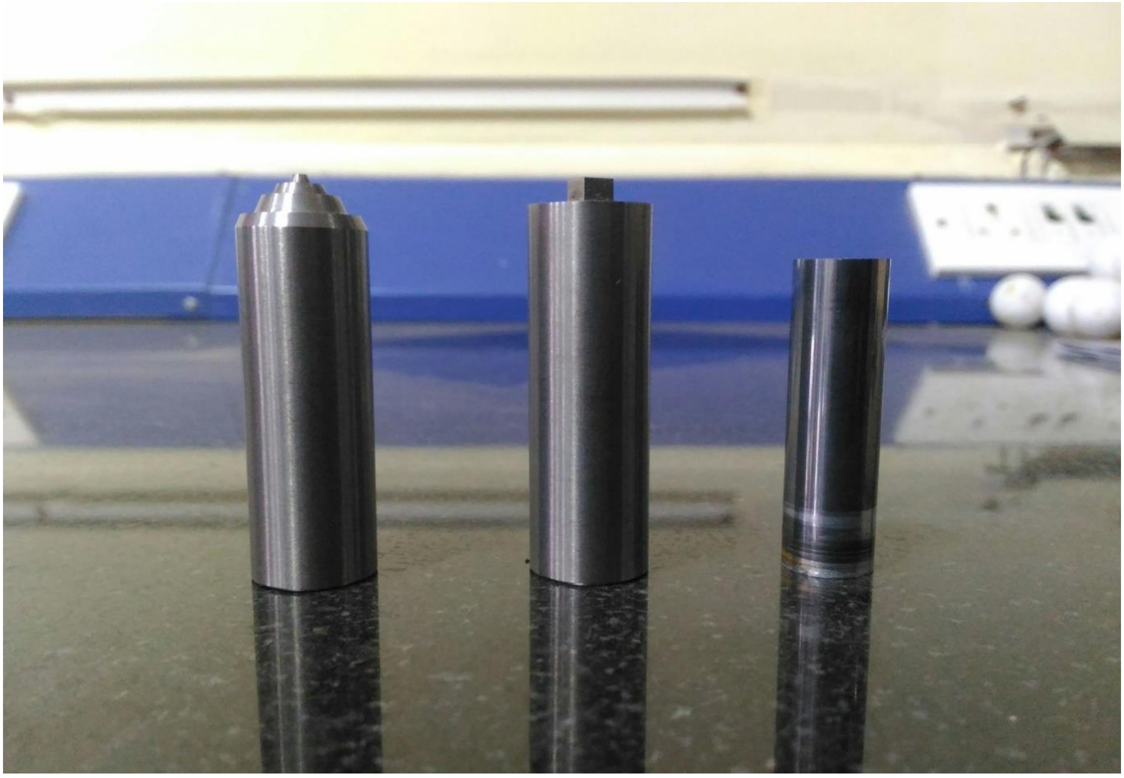


Fig 7: Manufactured tools

3.3 Design and manufacture of fixture:

The fixture is designed such that it can limit the vibrational and torsional forces acting during the additive friction stir processing. This is the Universal type of fixture where width and length of the plate held between the Z-clamps can be varied upto certain limits, whereas height of plate is fixed upto 6mm. The fixture consist of two Z-clamps and a base plate. The plate is fixed between the Z-clamps with the help of bolts provided. To provide a good torsional and vibrational properties the fixture is made of Mild-Steel with the additional galvanized coating. It is important that the workpieces should not spread or be lifted during the process; therefore, fixtures must be designed with features that are enable to achieve this objective. The quality of welding is dependent on the manufacturing precision of the clamping system and the welding table. Moreover, the impact of clamping process on the joint performance should be recognized so that the required constant quality could be ensured. The method of clamping and its effects on machine processes are well understood. Appropriate knowledge regarding the required forces would result in the chances of optimization of clamping system with respect to cost and efficiency. The 3-D model as shown in fig-8 is designed on Creo-parametric and the actual model is shown in fig-9.

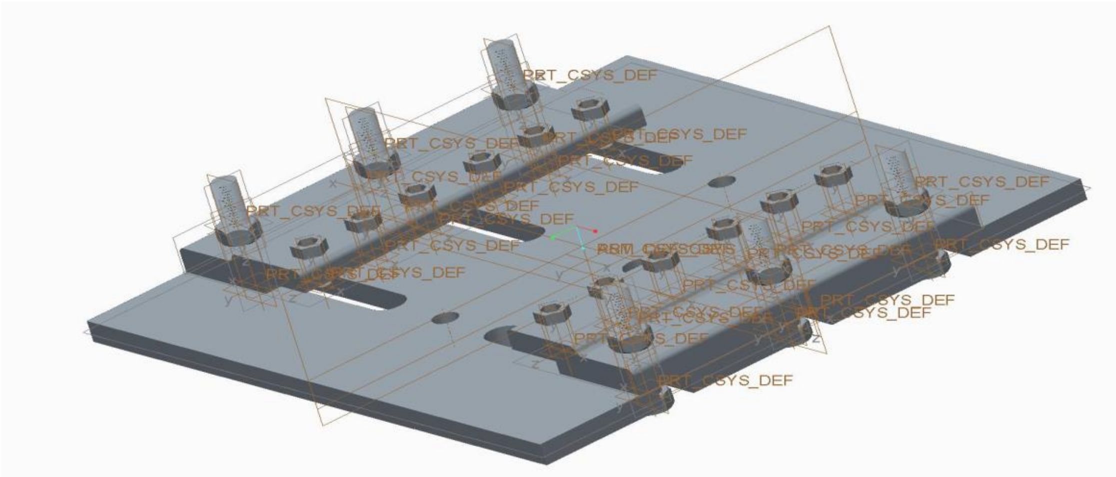


Fig 8: 3D model of fixture

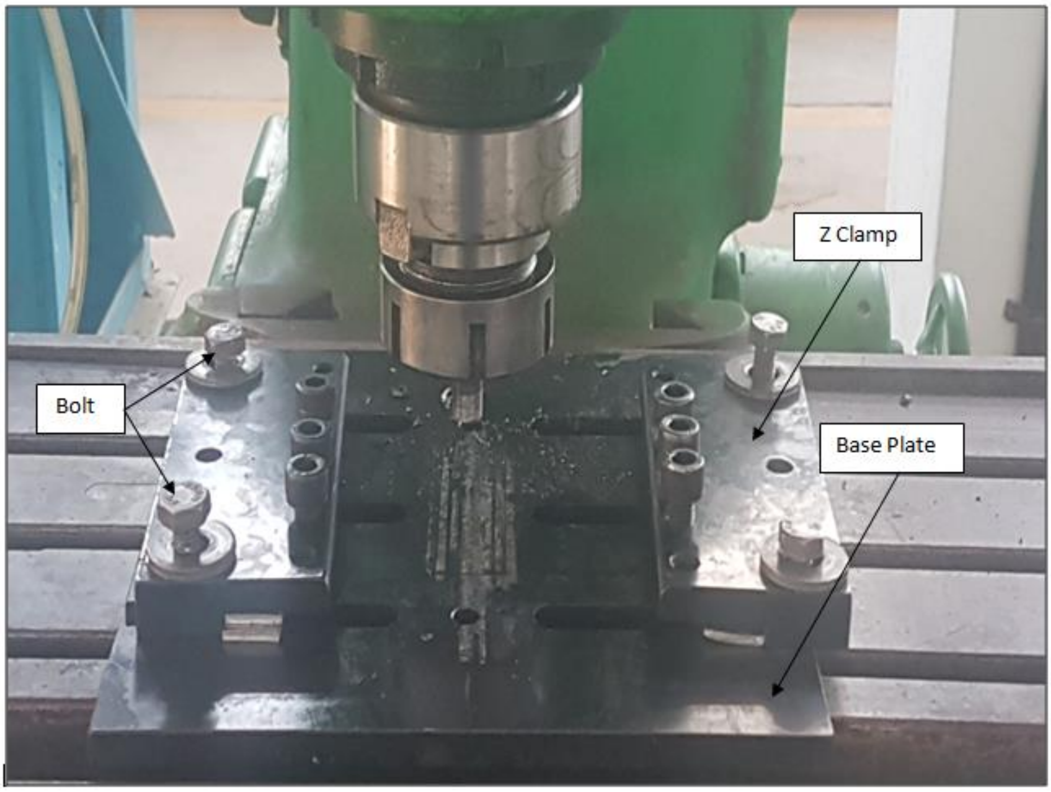


Fig 9: Actual Fixture

3.4 AFSP Parameters:

There are various parameters that are optimized during the experimentation of AFSP. Generally two or three parameters have been optimized to study the effect on grain size and surface microstructure. In this study we have optimized more than three parameters to study their effect on grain coarsening and microstructure. The following fig 11 shows the fish bone diagram, where the various parameters that governs the microstructure is mentioned.

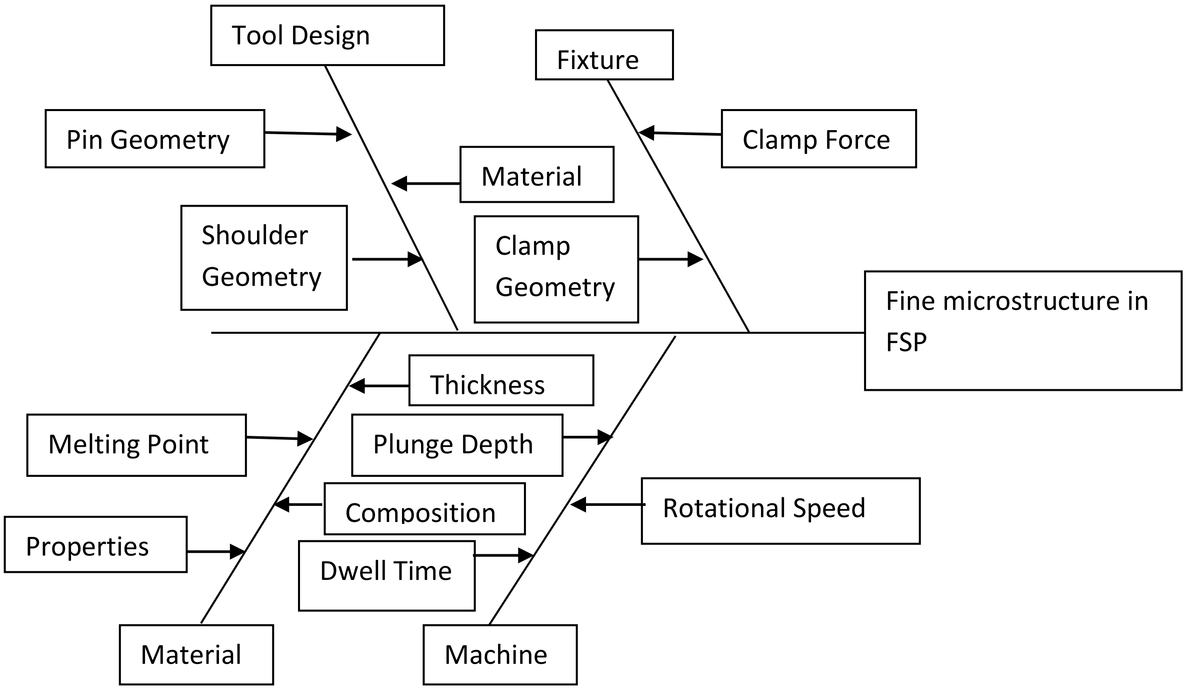


Fig 10: Fish bone diagram of FSP

Some of the parameters that are used to optimize are mentioned in Table-1. These parameters are then split into three sets, which are further used in combination for optimization.

Table 1: Parameters

SR.NO	Parameters of AFSP	I	II	III
1	Rotational speed	900	1150	1400
2	Transverse speed	30	40	50
3	Overlap	50%	60%	
4	Filler Material	Cu	CNT	SiC

From the above mentioned parameters different combinations are taken into consideration. These optimized parameters are then used for actual experimentation of AFSP. Taguchi method is further used after characterization to obtain best possible optimized parameters to retrieve better results.

3.5 Selection of Additives:

Filler materials are used to impart their properties over to the surface composite of 7075 Al alloy. Hence to obtain certain properties such as hardness, toughness etc. additives should be selected accordingly. Most commonly found additives are Ni, CNT, TiB_2, SiC, Cu etc. From amongst these additives CNT, Cu and Sic is used in this study for optimization. The following are the properties of the selected additives:

(I) **Carbon Nanotubes-**

- A carbon nanotube is a tube-shaped material, made of carbon, having a diameter measuring on the nanometer scale.
- A nanometer is one-billionth of a meter, or about 10,000 times smaller than a human hair.
- Carbon Nanotubes are used as filler material to increase surface hardness.

(**II) Copper (Cu):**

- Copper is used as precipitation hardening alloy.
- It is soft, ductile, malleable metal with very high thermal and electrical conductivity.

(III) Silicon Carbide (SiC):

- SiC has chemical stability, high thermal conductivity, smaller thermal expansion coefficient and better abrasion resistance.
- SiC consist of high mechanical strength. Its microhardness is 2840 ~ 3320kg/mm^2 and hardness is between corundum and diamond.
- It is a semiconductor and resistant to oxidation in high temperature.
- SiC is used in many applications such as strengthening materials for Al, Al_2O_3, Mg, and Ni also for polishing abrasive, high hardness grinding material etc.

4. EXPERIMENTATION SETUP:

4.1 Specifications of Vertical Milling Machine (DIAT):

The experimentation of FSW, FSP and AFSP is carried out on Vertical Milling Machine of DIAT. The following figure shows the components of the vertical milling machine.

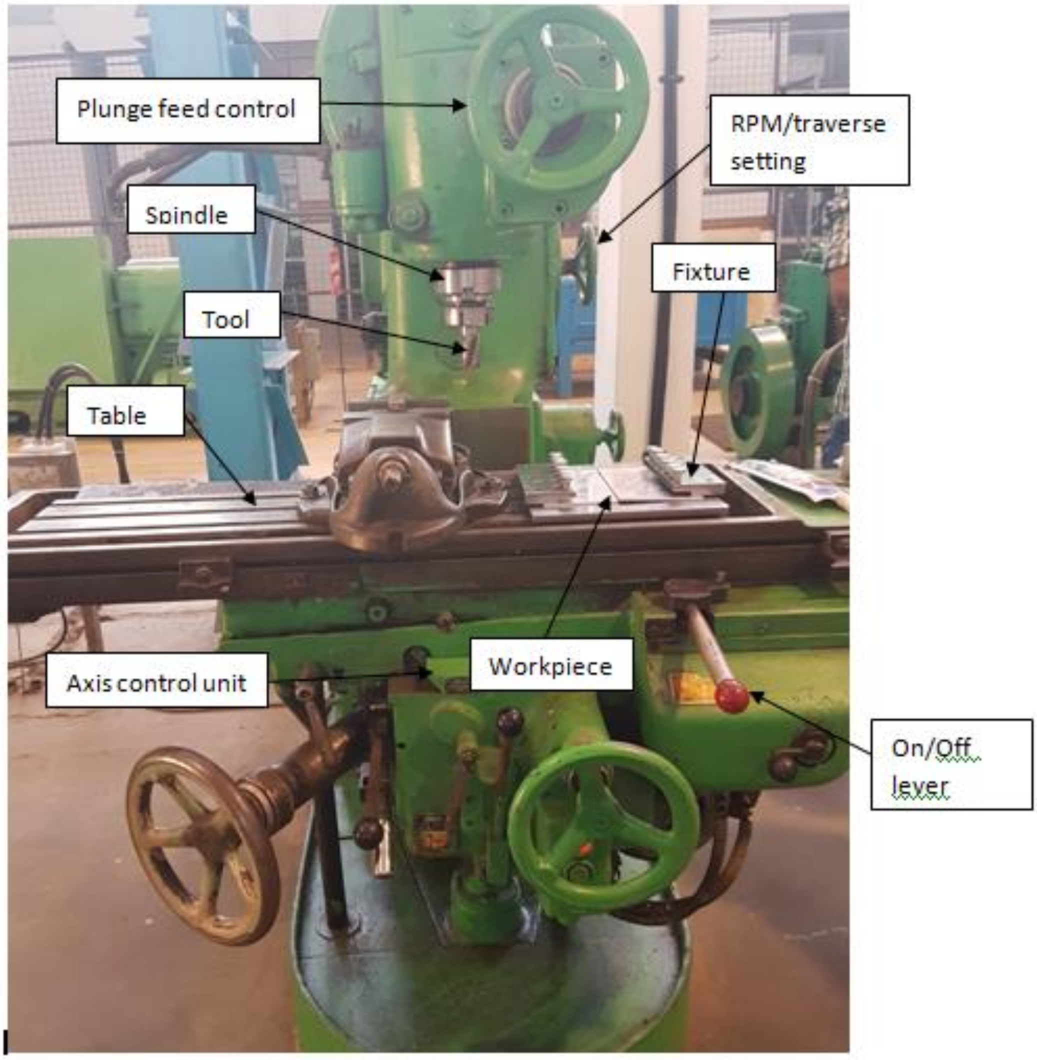


Fig 11: Vertical milling machine

Following are the specifications of the vertical milling machine shown in table-2

Table 2: Specifications of Vertical milling machine

Table	Axis Travel(inch)	X	Y	Knee	Quill	RAM
9x42	No power feed	26.82	12	13.78	5	13.39
	With power feed	23.69	12	13.78	5	13.39
9x50	No power feed	36.61	12	13.78	5	13.39
	With power feed	31.89	12	13.78	5	13.39

Stock options:

1. Model # **M2-S**
   16 Speed Step Pulley Spindle Head, 70 - 4620 RPM
2. Model # **M2-V**
   Variable Speed Spindle Head, 60-4200 RPM

UPGRADES & ACCESSORIES:

- Power Feeds
- Digital Readouts
- CNC Retrofit Kits
- 50 Watt Halogen H3 Work Lamp
- Coolant System With Chip Pan
- Auto Lube System
- Power Drawbar
- NT30, NT40 Spindle Tapers
- Vices, Collet and Clamping Kits
- Safety Hand Wheels
- Cutter Shields

4.2 Specifications of workpiece:

Table 3: Composition of 7075 Al alloy.

Component	Al	Cr	Cu	Fe	Mg	Mn	Si	Zn	Ti
Wt. %	87.32	0.28	2	0.5	2.9	0.3	0.4	6.1	0.2

4.3 Specifications of Tool:

Table 4: Tool Material used for FSW/FSP.

Sr.No	**Tool Material**	**Tool Configuration**
1	WC-Co (10%)	Square Tool Profile With Concave Shoulder.
2	Tool Steel (H13)	Tapered Cylindrical Tool With Thread And End Feature.

5. EXPERIMENTAL WORK:

As received material was with the specifications of (1m*1m). Aluminium is a soft material and light in weight, hence preparation of sample was easy. The operations carried out throughout the experiment is shown in the Table-5.

Sr.No	Operations	Machines Used	Objectives
1	Cleaning and Washing	-	To remove dirt and oil particles.
2	Cutting	Power Shear	To make standard size plate.
3	Marking and Slot making	1.Milling M/c (Metal Slitting cutter). 2.Hand Drilling M/C	To make slots and drills for powder filling.
4	Powder Filling	-	To conduct AFSP
5	Powder Locking	Vertical Milling M/C	To avoid scattering and pullout of powder during FSP
6	FSP/AFSP	Vertical Milling M/C (FSP Tool)	To obtain coarse grain microstructure and other project objectives as mentioned above.

1) Cleaning and Washing:

As received material had some dirt on the surface which needs to be removed to obtain the plate dirt free. The plate were washed with normal water and cleaned by using cotton cloth.

2) Cutting:

The material was sheared into smaller dimension of 170*75 mm. The shearing was carried out on Power Shear machine. As aluminium is soft material and light in weight its dose not require much time for shearing into small plates.

3) Marking and Slotting:

Marking is carried out after cutting and cleaning operation is done. The plate material are marked for the operations such as groove preparation and drill preparation. . The markings of on the plate material were carried out such a way that the AFSP and FSP processes were done alternately on the same plate by keeping the optimized parameters of the consecutive passes equal. The grooves and the drills are hand filled with the selected additives. The marking was done accordingly as shown in the fig-12 and fig-13.

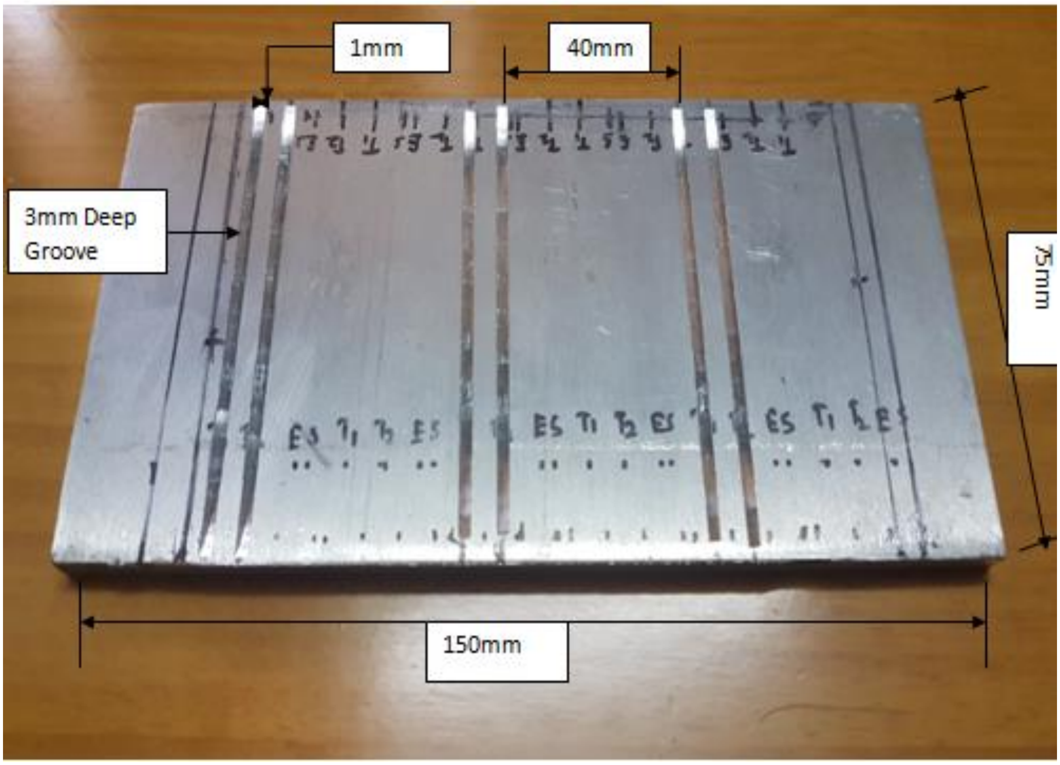


Fig12: Slotted plate

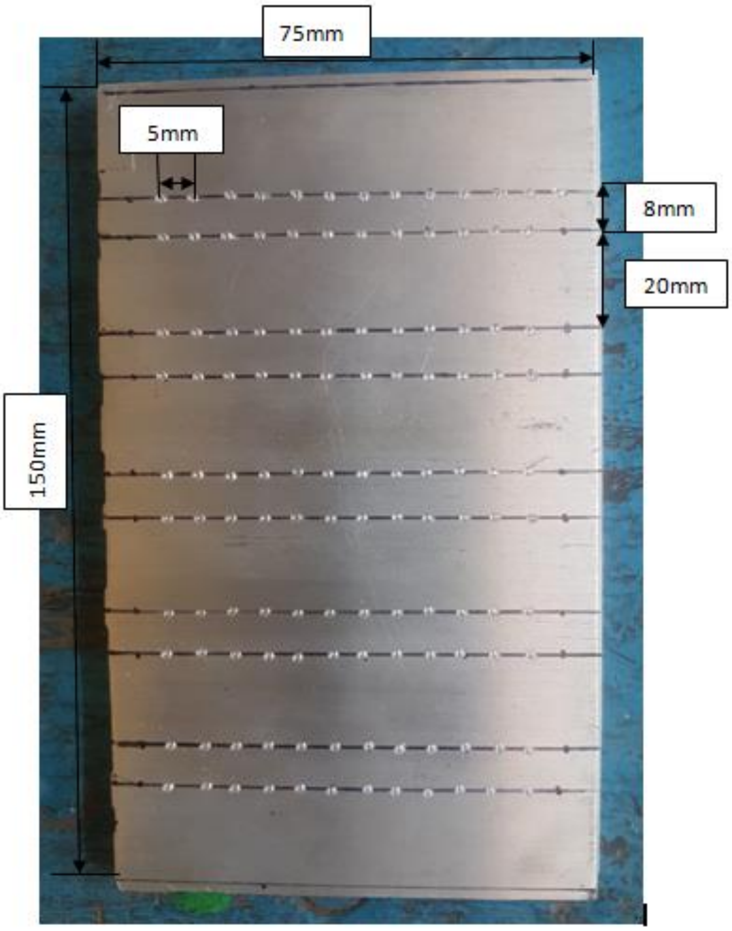


Fig 13: Drilled plate

(I) Grooving: The grooving of the plate material was carried out on grooving machine. A slot of 3mm was grooved longitudinally in the plate material.

(II)Drilling: The drilling of the plate was carried out on hand drilling machine. Due to soft material it does not take much time for drilling holes in plate material.

4) Powder Filling:

To achieve the AFSP, powder filling must be carried out. Ultra fine micro powder and nano particles such as CNT,SiC and Cu are filled in the slots which is used for AFSP. The powder is filled normally by using hand gloves, nose cover and glasses. Safety measures are ought to be taken during powder filling to prevent from itching and lung diseases.

5) Powder Locking:

To avoid scattering and powder to pullout the slots were locked using H13 pinless tool.

6) AFSP:

After preprocessing over the plate, workpiece is prepared for AFSP aswell as FSP. For the experimentation three plated were selected, consisting two plates of groove cutting and one of drilling. All three plates consists of different powders filled in their slots i:e CNT, SiC, Cu.

For Example: - Consider first plate with grooves upto 3mm of depth over the marked surface region. The grooves are then filled with the CNT powder with the gloves and the goggles as safety measures. The plate is then locked between the Z-clamps of the fixture. The powder is then locked with the help of H13 pinless tool to avoid scattering of powder while carrying out AFSP with the vertical milling machine. The AFSP is carried out longitudinal to the plate axis with a particular optimized parameters. The passes are performed accordingly from one end of the plate to the other end over the grooved and locked surface. The second pass is carried out with the 50% of overlap angle for better homogeneous grain microstructure. The FSP is also carried immediately after AFSP in nearby marked region by allowing same parameters as to the previous pass. After the processing of all the plates and passes are completed, plate undergoes sampling and sample preparation.

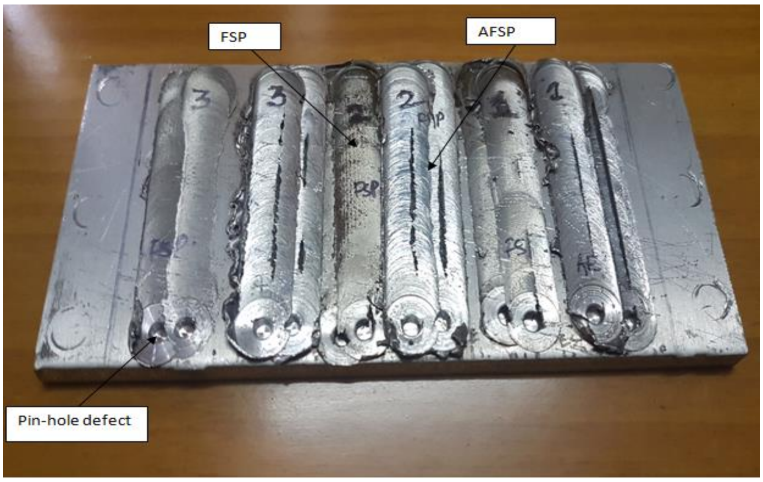


Fig 14: AFSP and FSP plate

6. Sampling and sample preparation:

The samples of dimension 10*10mm approximate are prepared with the help of abrasive cutting machine. The plate material is marked consisting of approximately 4 to 5 samples of 10*10mm on each pass. The samples of AFSP and FSP are collected simultaneously and are kept according to the specific parameters used over that pass.

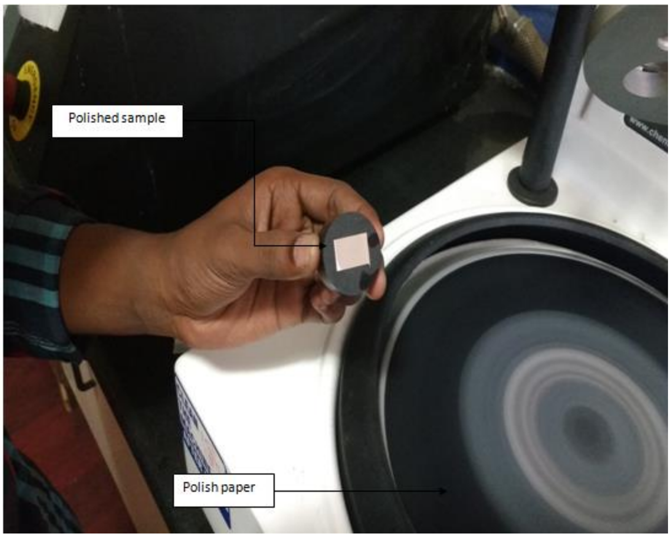


Fig 15: Sample Preparation

The cut samples prepared are further passed over for mounting, surface finishing, and preparation of etchant operations as mentioned below:

(I) Mounting:

Generally mounting are of two types i:e hot mounting and cold mounting. In this project hot mounting was used for sample preparation. Mountings were prepared in automatic hot mounting machines. Bakelite powder is used for sample preparation of hot mounting machine. The surface should be dust free and Two and half spoons of Bakelite powder was used for sample preparation. It takes around 17 to 20 minutes for preparation of sample mountings and 2 to 3 minutes for cooling of the samples. Then the samples are introduced for the surface finishing.

Fig 16: Hot Mounting machine

(II) Surface Finishing:

Surface finishing is essential process that is carried on every sample for getting best possible results of optical microscopy and other characterization techniques. In surface finishing technique every sample undergoes polishing over different polish papers starting from 260 and continuing accordingly i.e 400, 600, 800, 1200 and 2400. The polishing over the velvet paper is essential before applying etchant for characterization. Diamond paste is applied on the velvet paper before polishing in limited amount for giving a mirror finish to the sample surface.

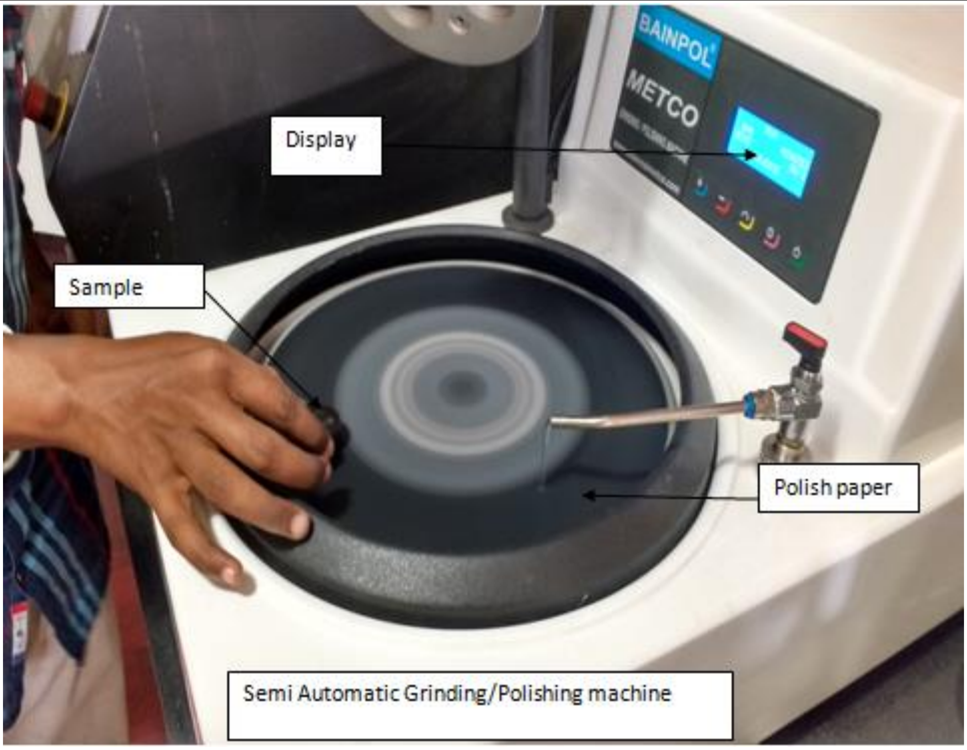


Fig 17: Surface Finishing

(III) Preparation of Etchant:

Etchant is used in microfabrication to chemically remove layers from the surface of a wafer during manufacturing. Etchant is a critically important process module. Etchant corrodes the grain boundary, which is intended to make a cavity in a material, to observe it under microscope. The depth of the cavity may be controlled approximately using the etching time and the known etch rate. The etchant used for 7075 Al alloy is 50ml 0f Kellers etchant. The composition of the etchant is given below in table-(6).

Table 6: Composition of Kellers Reagent:

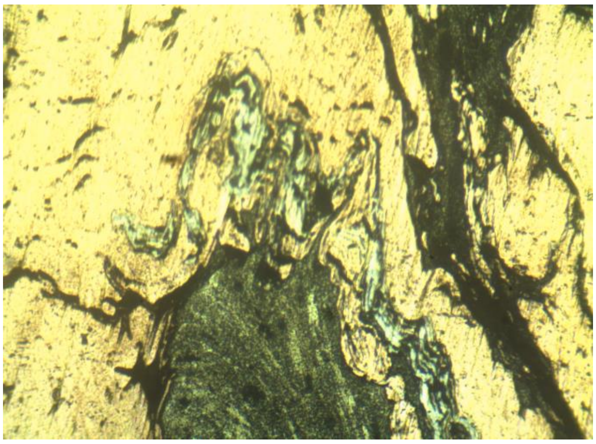
Sr.No	Solutions	Amount (ml)	Time of immersion
1	Distilled Water	47.5	10 to 30 sec
2	Nitric acid	1.25	
3	HCl	0.75	
4	HF	0.5	

7. DEFECTS:

Various defects are observed during the additive friction stir processing of 7075 Al alloy. Due to changes in optimized parameters few defects are observed such as Pin hole defect, Tunnel defect. Various factors affect the quality of friction stir processing such as tool tilt angle, fixture design, spindle rpm, traverse speed. Some defects may occur due to excessive vibrations generated by machine. Also if clamp bolts are not properly tight then there may be movement of plate which causes surface defects. Some defects may occur due tool wear. Following figures show the various defects occurred during friction stir processing of aluminium alloy

(A) Line Defect

(B) Pin Hole Defect



(C) Improper mixing of Cu additive in 7075 Al alloy during AFSP

Fig 18: Defects in additive friction stir processing

8. CHARACTERIZATION:

8.1 Optical microscopy:

The microstructures of the as-received specimen and with different combinations of the process parameters will be studied. Laser surface hardened samples for microstructure analysis would be cut in transverse section. These samples would be then subsequent polished (emery paper 230-2400). Then the samples would be lapped by using diamond paste. The black residue formed during lapping will be removed by running water, then dried and washed with cotton. The samples would be etched using 50ml Kellers etchant. The prepared samples would be analyzed using optical image analyzer. Grain boundaries, stir zone and defects produces during AFSP will be observed and analyzed under microscope.

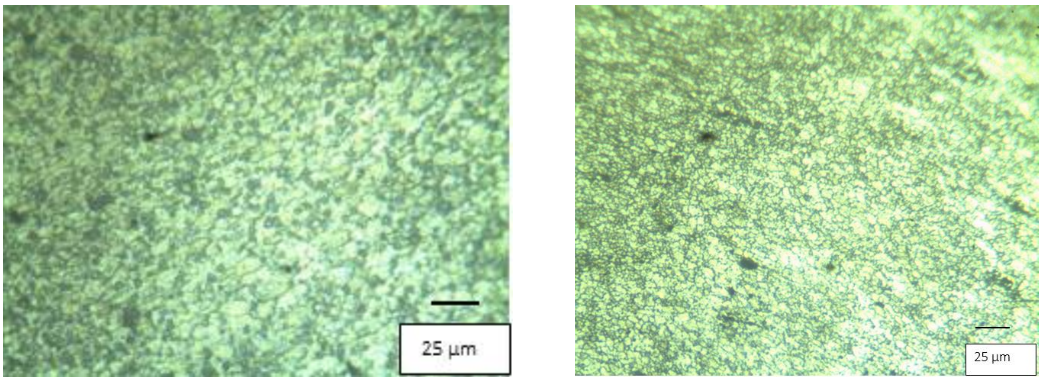


Fig 19: Optical microscopy of Cu(400x)and (200x)

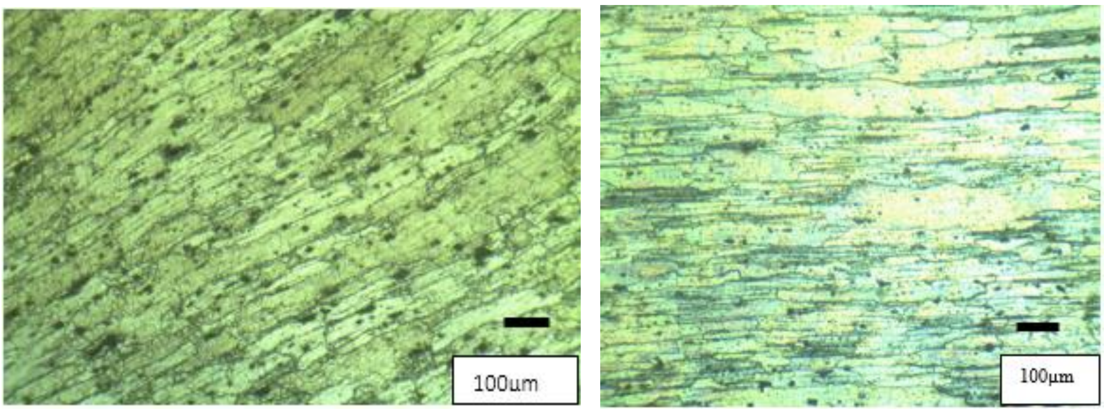
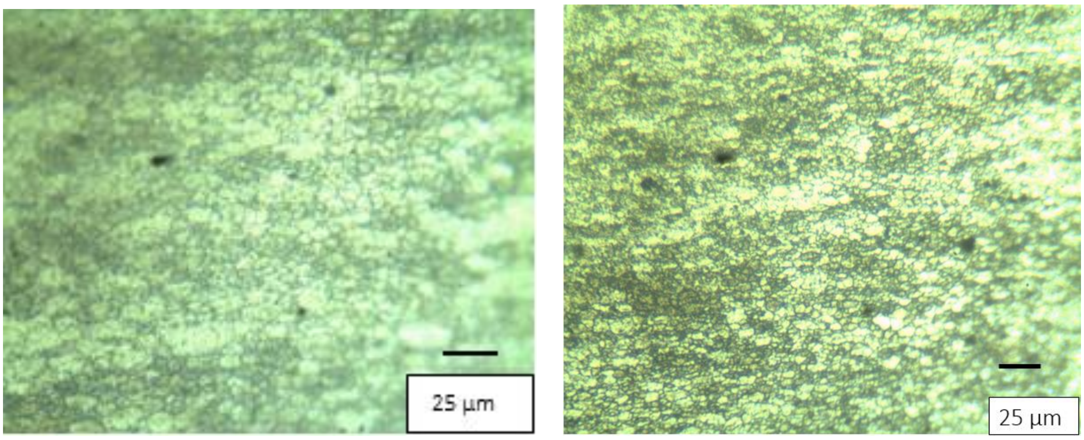


Fig 20: Optical microscopy for SiC particles(100x)



(a) 400x (b) 200x

Fig 21: Optical microscopy of CNT particles

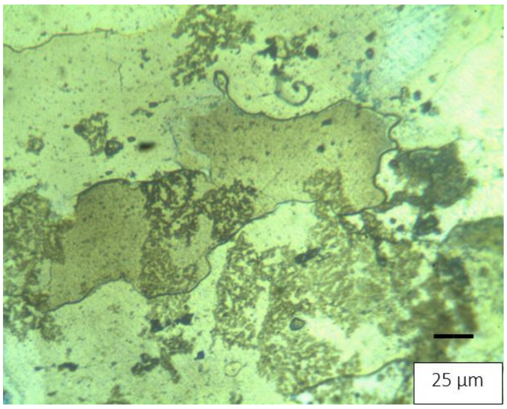


Fig 22: Optical microscopy of 7075 parent material

8.2 Scanning electron microscopy (SEM)

- A scanning electron microscope (SEM) is a type of electron microscope that produces images of a sample by scanning it with a focused beam of electrons.
- The electrons interact with atoms in the sample producing various signals that contain information about the sample's surface topography and composition.
- SEM can achieve resolution better than 1 nanometer.

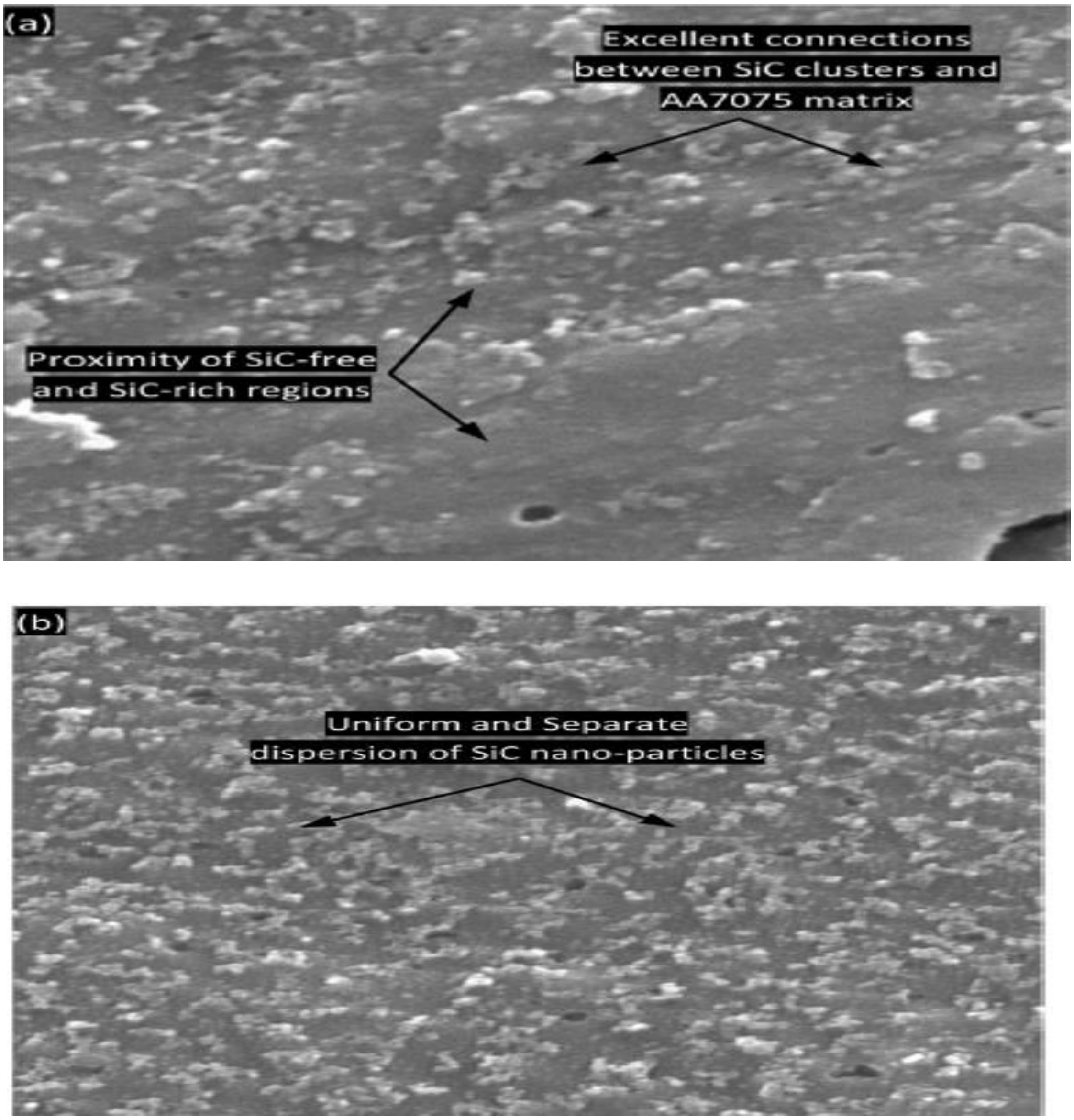


Fig 23: SEM image of distribution of SiC nanoparticles in Al 7075 matrix

Due to addition of SiC nanoparticles the enhancement in microstructure and properties of Al 7075 is seen in above SEM images.

8.3 Microhardness:

Hardness of Al 7075 alloy increases significantly when reinforced with various filler materials. Following is a graph showing increase in hardness of Al alloy due to addition of SiC particles of various size. From the graph we can say that as particle size decreases hardness of base metal increases.

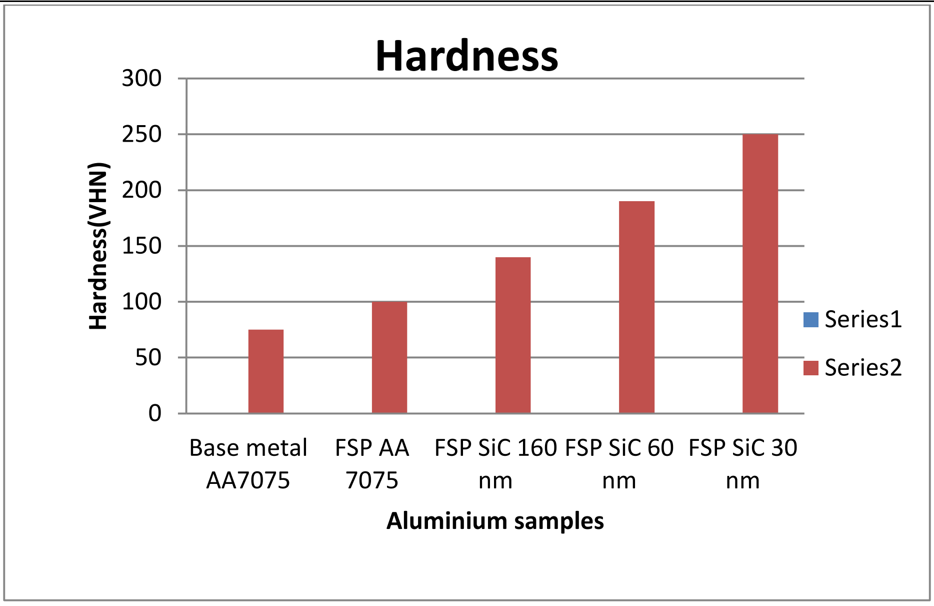


Fig 24: Microhardness vs. Aluminium samples

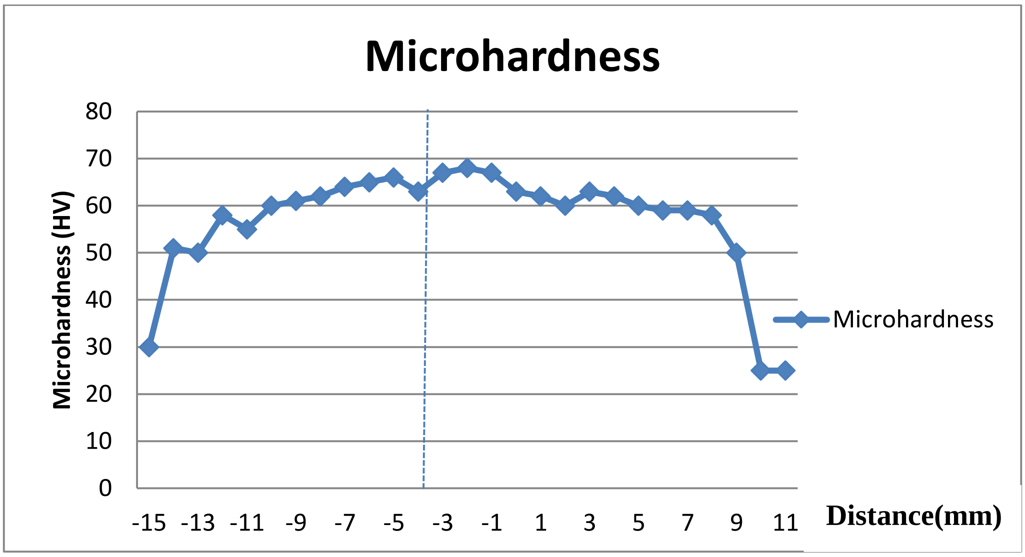


Fig 25: Microhardness vs. Distance

In the above graph variation of hardness with respect to position is shown. The centreline shown in graph with higher hardness is pin area. As we go away from centreline hardness decreases in shoulder area.

9. CONCLUSION:

1. By using Simple Cylindrical pin tool geometry, higher rotational speeds are required to get defect free processed zone, as material sticks to pin at lower rotational speed. Due to higher RPM heat generation is more which leads to grain coarsening in HAZ.
2. It was found that increasing the tool rotational speed improved the distribution of additive particles.
3. Due to addition of different types of additives in aluminium matrix surface properties are enhanced.
4. Due to addition of carbon nanotubes strength of Al matrix increased by twice its original value.
5. Silicon carbide is used for dispersion strengthening of aluminium alloy.
6. Due to additive friction stir processing grain refinement of aluminium alloys takes place which can be seen in optical microscopy.
7. Also the bonding between Al alloy and SiC particles can be seen in SEM.
8. Hardness of aluminium alloy increased significantly due to addition of carbon nanotubes and silicon carbide.

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