International Journal of Engineering Science Invention (IJESI)
ISSN (Online): 2319 – 6734, ISSN (Print): 2319 – 6726
www.ijesi.org ||Volume 4 Issue 06 || June 2015 || PP 81-105

Studying the Effect of Tool Geometries on Friction Stir Welds

Dr Himanshu Sekhar Moharana[1], Govind Chandra Dash[2], Rajat Kumar Panda[3]
[1] Professor, Department of Mechanical Engineering, Gandhi Institute For Technology (GIFT), Bhubaneswar
[2]Assistant Professor, Department of Mechanical Engineering, Gandhi Institute For Technology (GIFT), Bhubaneswar
[3] Assistant Professor, Department of Mechanical Engineering, Gandhi Engineering College, Bhubaneswar

Abstract: *The present investigation is aimed at development of friction stir welding (FSW) tool for industrial scale use more precisely for ship super structure fabrication. The proposed research will include experiments related to the effect of FSW tool geometry on weldability of Al alloy. The tools will be utilized in industrial scale FSW machine for investigating its effect on parameters like tensile strength, microhardness and grain refinement of friction stir Aluminium welds. Although much research work is going on in designing and development of FSW tool and machine, the process has not been standardized yet. As the FSW process is condition specific that means dependant on type of alloy, thickness of alloy, size of joint etc, it is difficult to have universal FSW set up. Hence for specific application like ship super structure fabrication which involves FSW of long thick and thin marine grade Al alloy. A FSW process has to be developed with a production rate acceptable to the industry. In the proposed investigation tools of different geometries will be designed and developed in house and will be tested for a definite Al alloy.*

I. Introduction

Friction Stir Welding (FSW) is a solid state welding method without using filler material in which the joined material is plasticized by heat generated by friction between the surface of the plates to be welded and the contact surface of a special tool, which is composed of two main parts; shoulder and pin. Shoulder is responsible for the generation of heat and for containing the plasticized material in the weld zone, while pin mixes the material of the components to be welded, thus creating a joint. This allows for producing defect-free welds characterized by good mechanical properties. The process uses a spinning non-consumable tool to generate frictional heat in the work piece. FSW creates weld by the combined action of frictional heating and mechanical deformation, the maximum temperature reached is of the order of 0.8 of the melting temperature. The Process is most suitable for critical applications like joining of structural components made of aluminum and its alloys.

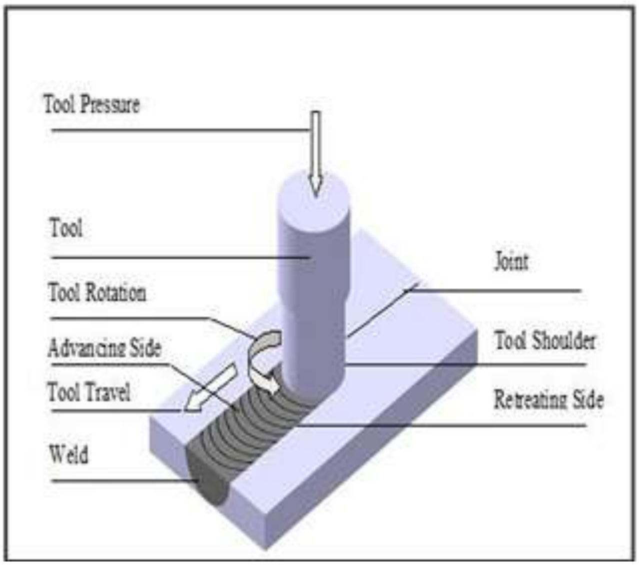


Figure 1.1: Friction Stir Welding Process.

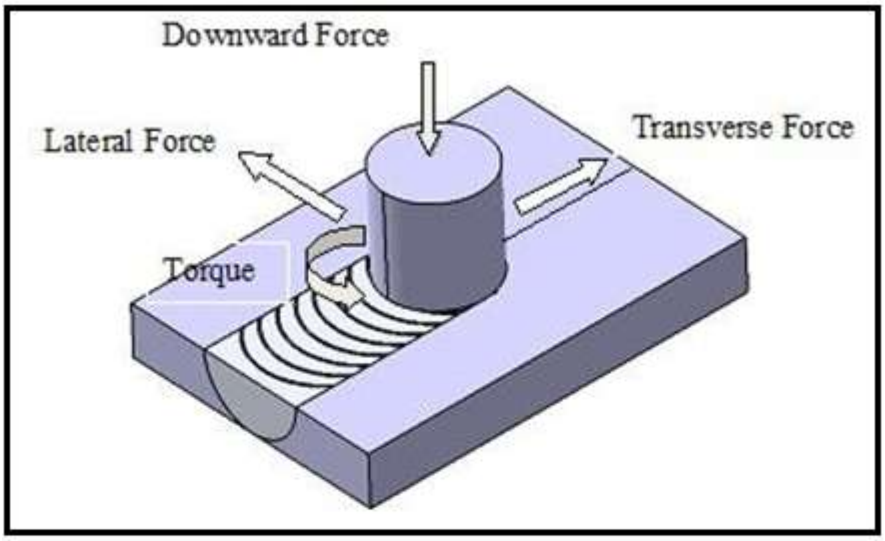


Figure 1.3: Forces acting on FSW Tool.

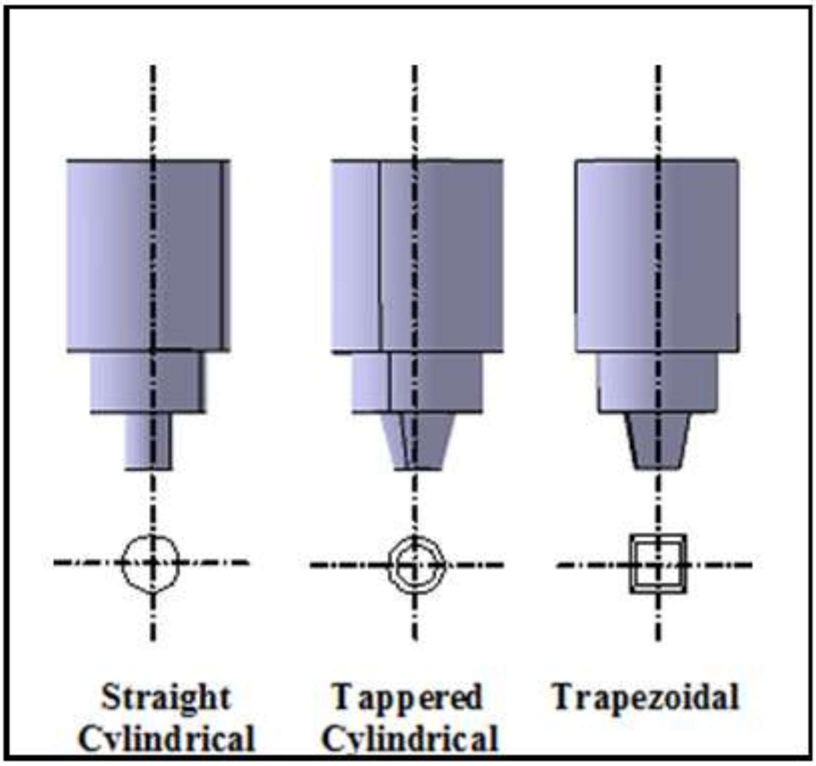


Figure 1.4: Tool Probe Profiles.

The history of joining metals goes back several millennia, with the earliest examples of welding from the Bronze Age and the Iron Age. From that time the process of welding gone through several modifications, world wars caused a major surge in the use of welding processes, with the various military powers attempting to determine which of the several new welding processes would be best. Many sophisticated welding methods for different alloys of variety applications are available now. In the present literature survey an attempt has been made to systematically examine the various research and literature available on Friction Stir Welding of aluminum alloys, the effect of tool geometry and process parameters (e.g. tool rpm and welding speed) on weld quality.

Wang D. & Liu S. [1] studied the Friction stir welding of aluminum: In this, the Aluminum plates were friction stir welded at various rotation speeds (850 – 1860 rpm) and travel rates of 30 to 160 mm/min with welding forces ranging from 2.5 to 10 MPa using different dimension welding heads. From the experiments it has found that dimensions of the welding head are critical to produce sound weld and the microstructure of the weld is characterized by its much finer and equi-axed grains as compared to the parent Aluminum plate. 10% higher micro-hardness is obtained than the parent metal. From all the experiments it was found that the travel rate of welding head pin has a strong effect on micro-hardness and tensile strength of the FSW welds.

Scialpi A., et. al. [2] studied the influence of shoulder geometry on microstructure and mechanical properties of friction stir welded 6082 aluminum alloy: In this work, the tool analysis has been carried out on AA 6082 T6 1.5 mm thick sheets and the welding process was carried out rotating the tool at 1810 rpm and at a feed rate of 460 mm/min.

Three types of shoulder geometries have been taken into consideration. From the experiments it was concluded that T_{FC} tool (tool with fillet and cavity) crown is the best in terms of crown quality. T_{FS} (fillet and scroll) and T_{FC} showed a higher strength and elongation respect to the T_F (only fillet). With 460 mm/min and 1810 rpm, TFC can be considered the best tool because the combination of fillet and cavity increases the longitudinal and transverse strength of the joint and provide the best crown surface.

Fujii H., et. al. [3] studied the effect of tool shape on mechanical properties and microstructure of friction stir welded aluminum alloys: The objective of this work is placed on to determine the effect of the tool shape on the mechanical properties and microstructures of the FSW joints. The simplest shape (column without threads), the ordinary shape (column with threads) and the triangular prism shape probes were used to weld three types of aluminum alloys. The conclusions achieved were for 1050-H24 whose deformation resistance is very low, a columnar tool without threads produces weld with the best mechanical properties. For 6061-T6 whose deformation resistance is relatively low, the tool shape does not significantly affect the microstructures and mechanical properties of the joints. For 5083-O whose deformation resistance is relatively high, the weldablity is significantly affected by the rotation speed. At a high rotation speed (1500 rpm), the triangular prism tool is the best; at the middle rotation speed (800 rpm), the column with threads is the best, while for a low rotation speed (600 rpm), the tool shape does not significantly affect the microstructures and mechanical properties of the joints.

Boz M. & Kurt A. [4] studied the influence of Stirrer Geometry on Bonding and Mechanical Properties in friction stir welding process: In this, the effect of stirrer geometry on the weldability and mechanical properties of welded aluminum plates using FSW process was investigated. Welding processes were carried out with five different stirrers, four of them were screw type with 0.85, 1.10,1.40 and 2.0 mm pitch and one was a bar with 5mm X 5mm square cross-section. The 1.40mm and 2.0 mm pitched stirrers acted like a drill rather than a stirrer and compelled the weld metals outwards. As a result of this weld metal was accumulated towards the stirrer shoulder and therefore the welding process could not be affected. The best bonding was obtained with 0.85 and 1.10 mm pitched stirrers. Specimens welded using 0.85 and 1.10 mm pitched stirrers exhibited the same mechanical and metallographic properties. The square cross-section stirrer showed poor mechanical and metallographic properties. The specimens welded using 0.85 and 1.10 mm pitched stirrers exhibited 110 N/mm2 UTS and fractures took place in the base metal.

Cabibbo M., et. al. [5] studied the microstructure and mechanical property studies of AA6056 friction stir welded plates: In this work, the author has investigated the microstructure and mechanical properties of a friction stir welded 6056-T6 aluminum alloy plate by using polarized optical and transmission electron microscopy techniques. In this study FSW has been carried out for 10-mm thick plates at a rotational speed of 1800 rpm and an angle of 3° and with a translational speed of 15 mm/s. The conclusions obtained from the above experimentations are that the grain structure is fine equiaxed in the nugget at the weld centre, highly elongated with very small cells in the retreating side TMAZ and in the narrow advancing side, and slightly elongated coarse grains in the HAZ and the parent material.

Sarsilmaz F. & Caydas U. [6] studied the **s**tatistical Analysis on Mechanical Properties of Friction Stir Welded AA1050/AA5083 couples: In this, the effect of friction stir welding parameters on the mechanical properties of Aluminum alloys as investigated. The parameters taken into consideration are spindle rotation speed, traverse speed and stirred geometry. The ultimate tensile strength and hardness of the welded joints are determined. The conclusions drawn from the above experiments are the ultimate tensile strength and nugget hardness increases with traverse speed but decreases with tool rotational speed. The most important factor on ultimate tensile strength was found as traverse speed, then the rotational speed and finally the stirrer geometry. The most important factor on nugget hardness was found as traverse speed, then the rotational speed and finally the stirrer geometry.

Sakthivel T., et. al. [7] studied the **e**ffect of Welding Speed on Micro-structure and Mechanical Properties of Friction-stir Welded Aluminum: In this present investigation aluminum welds were made at various welding speed using the friction stir welding technique by using a hardened steel FSW tool. The welds are characterized for mechanical properties and micro-structural investigation. The conclusion drawn from the above study is that the micro-structure of the weld nugget consists of fine equiaxed grains and are more homogenous at lower welding speed than at higher welding speed. The size of the weld zone becomes wider when decreasing the traverse speed as a result of a large amount of frictional heat easy material flow but the hardness slightly increases with the increase of welding speed. The ultimate tensile strength is observed to increase when decreasing the traverse speed. The best mechanical properties are obtained at lower traverse speed due to the occurrence of homogenous grains and higher heat input.

Adamowski J. & Szkodo M. [8] studied the friction-stir-welds (FSW) of Aluminum alloy AW6082-T6: In this paper the properties and micro-structural changes in friction stir welds in the aluminum alloy 6082-T6 in function of varying process parameters have been investigated. In this study the test welds are produced with various combinations of process parameters without the possibility of controlling the downward force. Tensile tests of the produced joints were tested and the correlation with process parameters was assessed. Micro-structures of various zones of FSW welds are presented and analyzed by means of optical microscopy and micro-hardness measurements. The conclusions obtained from all the above experiments are mechanical resistance of test welds increased with the increase of travel speed with constant rotational speed. Softening of the material in the weld nugget and heat affected zone was observed i.e. the hardness of both the heat affected zone and the weld nugget is lower than that of the base metal.

Rodrigues D. M., et. al. [9] studied the influence of Friction Stir Welding Parameters on the Micro-structural and Mechanical properties of AA 6016-T4 Thin Welds: In this present work friction stir welds produced in 1 mm thick plates of AA6016-T4 aluminum alloy, with two different tools, were analyzed and compared concerning the micro-structure and mechanical properties. For each tool the welding parameters were optimized in order to achieve non-defective welds. From the above investigation done it was concluded that the differences in tool geometry and welding parameters induced significant changes in the material flow path during welding as well as in the micro- structure in the weld nugget. The welds produced shoulder displayed a larger nugget grain size with few coarsened precipitates as opposed to the welds done with the scrolled shoulder which showed a smaller grain size containing many coarsened precipitates. The differences in micro-structure conducted to a reduction in hardness around 15% in the cold welds contrary to the hot welds where an even match condition was reached. Despite the mechanical heterogeneity, the cold weld blanks displayed good deep drawing behavior.

Kim Y.G., et. al. [10] studied the effect of Welding Parameters on Microstructure in the Stir Zone of FSW Joints of Aluminum die Casting Alloy in this study the effect of the welding speed and the rotation speed on the microstructure in the stir zone has been investigated by measuring the Si particle distribution in the Aluminum die casting alloys which are made by the rapid injection of molten metal into metal molds under high pressure. The conclusions obtained from the above experimentations are that the stir zone has fine recrystallized grains without a dendritic structure and the number of finer Si particles increases during the FSW. The size of the Si particles in the bottom is smaller than that in the top or the middle, while the size in the retreating side is almost the same as that in the advancing side. The Si particles size decreases with the increasing welding speed.

Sato Y. S. & Kokawa H. [11] studied the distribution of Tensile Property and Micro- structure in Friction stir Weld of 6063 Aluminum: The objective of the present study is to clarify dominant micro-structural factors governing the global tensile properties of the welded joint by estimation of the distribution of the local tensile properties in the joint including extensive regions from the stir zone to the unaffected base material region. In this study an extruded 6063-T5 Al, 4 mm thickness plates were friction stir welded keeping the travel speed and the tool shoulder diameter were 10 mm/s and 15 mm respectively. The conclusions are that the minimum hardness determined global yield and ultimate tensile strengths of the welded joint. A tensile fracture occurred in the minimum hardness region in a joint having heterogeneous hardness such as an as- welded joint.

Yeni C., et. al. [12] studied the effect of Post Weld-aging on the Mechanical and Micro- structural Properties of Friction-stir Welded Aluminum alloy 7075. Here the authors have examined the effect of post weld aging for different helix angles and shoulder diameters. Exactly the effect of post weld aging on tool geometry, micro structural examination, hardness measurements and room temperature tensile tests have been carried out. The welding was carried out using two different helical angles of the threaded pin, namely right and left helicals and for right helical pin, two different shoulder diameters has been utilized. The conclusions obtained from above experiments are, the nugget zone exhibited a recrystallized fine grain structure with grain sizes increasing moving from the weld region to the base metal, post weld aging process compensates the hardness decrease observed in as welded joints; no significant decrease in hardness is obtained throughout the weld region. It has been seen that left helical screw yields higher mechanical properties when tested at the same shoulder diameter.

Rhodes C. G. et. al. [13] studied the fine-grain Evolution in Friction-stir Processed 7050 Aluminum: The objective of the present study was to get an idea about the detail evolution of the fine grains found in friction-stir processed 7050Al using a rotating- tool. The results indicate that the fine grains are initiated by recrystallization. The increase in tool speed from has resulted in increased deformation as well as increased frictional and deformation heating to the extent that recrystallization has occurred. The heat generated by the rotating tool is a function of the rotation speed and the external cooling rate. At slower cooling rates and/or faster tool rotation speeds, recrystallization of the deformed aluminum occurs.

Durdanovic M. B. et. al. [14] studied the effect of heat Generation during Friction-stir- welding (FSW) process: FSW works in the solid state of weld metals and basic goals of the process are to generate thermal energy by friction on contact of FSW tool and welding pieces, which will soften weld pieces and stir it with solid metal into weld. Generated heat is in proportion with large number of parameters, but most significant are contact pressure between tool-weld pieces and speed. In this paper the author has developed a mathematical model which describes the thermal generated in various stages of FSW. Parameters involving proper welded joint creation are just the same parameters in heat generation and this amount is directly dependable from the geometrical parameters of the tool, speed-rotational and traversal, pressure, shear stress and friction co-efficient. It is concluded from various models that determination of precise amount of heat generated during friction stir welding process is complicated since there are various uncertainties, assumptions and simplifications of mathematical models that describes the welding process.

Hwang Y.M., et. al. [15] studied the experimental study on temperature distributions within the workpiece during friction stir welding of aluminum alloys: In this study the thermal histories and temperature distributions in a workpiece during a friction stir welding (FSW) process involving the butt joining of aluminum 6061-T6 has been experimentally explored. Different types of thermocouple layout are devised to measure the temperature histories during FSW at different locations on the workpiece in the welding direction. Regression analyses by the least squares method are used to predict the temperatures at the joint line. From the regression analysis results it is known that the temperatures inside the pin can be regarded as a uniform distribution and that the heat transfer starts from the rim of the pin to the edge of the workpiece, approximately following a second-order polynomial equation. The appropriate temperatures for a successful FSW process are between 365 and 390 °C. The temperatures on the advancing side are slightly higher than those on the retreating side. The tensile strength and the hardness at the thermo-mechanically affected zone (TMAZ) are about one-half of the base metal.

Fonda R.W., et. al. [16] studied the initial Microstructural Evolution during Friction Stir Welding: In this study an aluminum single crystal was friction stir welded in four different directions. This study represents the first-ever investigation of friction stir welds in a single crystal material, and is crucial for understanding the fundamental processes that occur during this welding process. The conclusions drawn from the above work is that the shear deformation generated by the welding process gradually rotates regions of the single crystal, which grow in size and mis-orientation as the welding deformation continues. This rotation continues until these new grains achieve an easily-sheared orientation.

McNelley T. R. et. al. [17] studied the recrystallization mechanisms during friction stir welding/processing of aluminum alloys: In this paper two of the restoring models for hot working of metals are used to interpret microstructure and micro-texture data for two aluminum alloys subjected to FSP. Though two different plausible mechanisms have been identified in determining the SZ microstructures of AA2099 and AA5083 after FSP, it has to be recognized that these results were obtained on the materials that had different initial conditions and were subjected to different processing as well as tool parameters. From above experiments it is concluded that by friction stir process due to recrystallization grain refinement occurs.

Cerri E. & Leo P. [18] studied the warm and room temperature deformation of friction stir welded thin aluminum sheets; In this paper Friction stir welded joints of 2024T3– 2024T3, 6082T6–6082T6 and 6082T6–2024T3 of very thin thickness (0.8mm) were investigated at room and warm temperatures of deformation by tensile tests and microhardness measurements. The conclusion drawn from the above work is that all the thin FSW joints showed the capability to undertake tensile stress at room temperature and at warm temperatures of deformation. The stress has decreased with increasing temperature and decreasing strain rate. The ductility of the thin joints was quite independent of temperature and strain rate. Substantial modifications in grain size resulted during the FSW Process. Tensile specimen fractured in the middle of the stir zone after straining at room temperature or at warm temperature of deformation in a ductile mode.

Sato Y. S. et. al. [19] studied the micro-texture in the Friction stir Weld of Aluminum Alloy: In this paper the micro-texture in a friction stir weld of the precipitation- hardened aluminum alloy 6063 have been analyzed by orientation imaging microscopy (OIM) in order to characterize plastic flow during friction stir welding. The base- material plate used in the present study was an extruded Al alloy 6063-T5, whose thickness is 4 mm. The plates were friction stir welded such that the welding direction was parallel to the extrusion direction and the axis of the hard pin was tilted a few degrees from the plate normal direction. Optical microscope observations show that fine equiaxed grains occupy the weld center region and deformed grains exist just outside the weld zone. The weld center is characterized by the recrystallized grain structure and is mainly generated by dynamic recrystallization during friction stir welding.

Ma Z. Y. [20] studied the friction Stir Processing Technology: Friction stir processing (FSP), developed based on the basic principles of friction stir welding (FSW). From the above investigation it was concluded that intense plastic deformation and thermal exposure during FSP causes the creation of fine, uniform, and pore-free structure. The FSP causes intense plastic deformation, material mixing, and thermal exposure, resulting in significant microstructural refinement, densification, and homogeneity of the processed zone. FSP is energy efficient, environment friendly, and versatile, and can be developed to be a generic metalworking technique that can provide the localized modification and control of microstructures in the near-surface layers of processed metallic components.

Bhadesia H.K.D.H. & DebRoy T. [21] studied the critical assessment of Friction Stir Welding of Steels: This paper has contributed to the understanding of the FSW of steels. From the experiments it has been found that any of the tool technologies available today for the FSW of steels cannot be reused. The biggest problem in the industrial exploitation of FSW for steels is the development of a reliable, lasting and cost effective tool material. In this paper the authors have commented on the difficulties in FSW, which are easy to recognize, but it is useful to speculate on the more difficult task to identify the joining problem for steel.

Lienert T. J. et. al. [22] studied the friction Stir Welding Studies on Mild Steel: Results of this study have demonstrated the feasibility of Friction Stir Welding for joining of mild steel. The conclusions made from the above experiments are that Defect-free welds were produced on of 6.35-mm thick mild steel with FSW over a range of travel speeds from 0.42 to 1.68 mm/s. Tool loads during FSW of mild steel at 0.42 mm/s were approximately 18.7 kN, while measured torques were in the range of 55 Nm. Peak surface temperatures close to 1000°C (1832°F) were measured on the tool above the shoulder during FSW using thermocouples. Comparisons before and after welding combining both metallographic and metrology techniques suggest changes in tool dimensions resulted from both rubbing wear and deformation of the tool and the greatest changes in tool dimensions occurred during the initial plunging stage. The weld region displayed several micro structurally distinct regions including the stir zone (along the weld centerline), a grain-coarsened region (surrounding the stir zone), a grain-refined region (encompassing the grain-coarsened region).

Fonda R.W. & Bingert J.F. [23] studied the Micro-structural Evolution in the Heat- Affected Zone of a Friction Stir Weld: In this study the author has investigated the thermo-mechanically affected zone/heat-affected zone (TMAZ/HAZ) boundary of a friction stir weld in 2519 Al to determine their contributions to the properties of that region. Two plates of 25-mm- (1-in.-) thick 2519-T87 aluminum were friction stir welded along the rolling direction with a conventional pin tool under load control. The welding was performed with a rotational speed of 175rpm and a tool translational speed of 1.1 mm/s (3.5 in./min). The microhardness map revealed that the soft band, corresponding to the typical fracture location in friction stir welds of this alloy, is located at the boundary between the TMAZ and HAZ. The primary cause of softening at the TMAZ/HAZ boundary was determined to be due to coarsening and transformation of the strengthening precipitates during the welding process. Locations within the TMAZ achieve temperatures during welding that are sufficient to at least partially dissolve the precipitates, leading to the precipitation of very fine GP zones during cooling. It is these GP zones that produce the observed hardening and strengthening in the TMAZ.

Attallah M.M. et. al. [24] studied the Microstructure-microhardness relationships in friction stir welded AA5251: In this work microstructural studies using optical and electron microscopy were carried out to determine the grain size and inter metallic particle distributions in various locations of friction stir welds in AA5251 to study their influence on the microhardness. The base material used in this study was AA5251 5 mm thick sheets and the welding parameters were a rotation speed of 500 rpm and traverse speed of 500 mm/min. After distinguishing the various influences, it was found that the TMAZ/WN strength was found to be primarily controlled by grain boundary strengthening. Despite the high dislocation stored energy measured in the TMAZ/WN compared to the base metal, the high stored energy was associated mainly with geometrically-necessary dislocations resulting from the grain refinement and presence of inter metallic particles as a result of the large strain deformation during FSW.

Meng Z. et. al. [25] studied the Optimization of Stir Head for FSW based on Genetic Algorithm: In this work the shape selection of stir head is processed to Friction Stir Welding (FSW), and the mathematical model and constraints for the optimization of stir head are established and the multi-target optimization algorithm of stir head dimension based on genetic algorithm is presented. The cone screw stir head has been selected according to the analysis to its advantages. The mathematical model for the optimization of stir head is established, which has been treated as the optimized objective function.

E. Sukedai et. al. [26] has carried out Micro-structure analysis of a friction-stir welded 2024 aluminium alloy using electron microscopy: In this work FSW was performed under a condition of tool tilt angle = 3 degrees, rotation speed = 1,300 rpm and welding speed = 330 mm/min and thin foil specimens from the nugget and the mother material were prepared. Micro-strucutre observation and EDS analysis were carried out using a JEM 2010F electron microscope. An EDS spectrum of a rod-shape precipitation in the nugget, and Al, Cu, Mn, Cr, Si and Mg were detected. In the round-shape precipitation in the same area, Al, Cu, Fe and Mn were detected, but Si and Mg were hardly detected.

II. Chapter – II1 Experimental Investigation

CHAPTER – III
EXPERIMENTAL INVESTIGATION

The friction stir welding (FSW) experiments were conducted at Ocean Engineering and Naval Architecture Department, IIT Kharagpur. The experiments were conducted on a specialized friction stir welding machine having torque and vertical load sensors. The FSW tools were the vital part of the investigation as the tools were designed and manufactured for the purpose. The FSW experimental investigations carried out during the present investigation can be broadly categorized into following steps.

- Initial trials using a conventional milling machine.
- Augmenting the machine to get the required rigidity and toughness for applying the vertical load.
- Trials of jobs using FSW tools made of mild steels.
- Trials of jobs using the FSW tools made of die tool steels.
- Trial of jobs using stainless steel FSW tool.
- Using proper process parameter for getting the acceptable weld.
- Testing the samples for tensile strength, grain structure and microhardness.

3.1 Initial Trials using a Conventional Milling Machine:

A conventional vertical milling machine was used initially for testing the possibility of FSW of aluminum alloy. The experiments were conducted by using the maximum setting of the machine and it was found out that the machine setup was inadequate. The machine lacked sufficient rigidity and the motor power was inadequate for applying the required power to rotate the tool while welding the alloy.

Hence it was decided that the machine needed to be replaced or improved to successfully weld the alloy. It was found out that the vertical pressure applied during the FSW is important as it presses the FSW tool to the plate surface to be welded. The FSW tool is also rotated and the bed of the machine on which the job is attached traverses. Hence, the spindle which houses the rotating FSW tool must be rigid enough and supplied with enough torque such that the tool will initially pierce into the metal and stir the metal.

Once the stirring starts, the tool is required to travel along the weld line. The traversing arrangement should be such that various traversing speeds can be set with respect to the vertical pressure applied and the rotation of the tool. The clamping arrangements of the plates to be welded should be such that it can withstand the vertical pressure and the traversing of the tool along the weld line. For very thin sheets a geared drive with 5 HP motor might be suitable. But for thickness above 2 mm it was found out that at least a geared motor of 10 HP is required. Such arrangements requires excessive refitting of the machine involving high power drive motor whose revolution rate can be controlled continuously. Hence the speed control of the vertical motor has to be specially designed for a range of variation of RPM.

3.2 Augmenting Machine to get the Required Rigidity & Toughness for Applying Vertical Load:

The machine capability was improved by incorporating the new power drive for a better torque and rotational speed. The power of the new drive was such that the rotation of the FSW tool in the initial stages was sufficient to induce frictional heating while rotating. The power drive chosen was also adequate to induce the stirring effect in the joint. The stirring effect is the most important characteristics of the FSW process.

The stirring effect actually induces the necessary grain refinement to the FSW process which distinct the process from conventional arc welding process. The machine traversing arrangements was also improved by fitting more powerful traversing gears. The machine was improved such a way that the backlash during the process is minimum. The vertical axis back lash was minimized to facilitate accurate depth of penetration of the FSW tool in the job.

The augmented machine also posed a challenge to fix the job to the base plate of the machine. The plates/jobs were to be rigidly clamped. The clamping system was developed such that the plates would not get loose by the vertical pressure applied to the joints during the welding process. The augmented machine also had to be with adapter arrangements for a range of FSW tool diameters. The FSW tool adapters were chosen such a way that various diameter of tools can be fitted into it.

The segmented machine was trialed with low rotation speed high vertical pressure and high rotational speed low vertical pressure. The machine was also trialed for high vertical pressure and high rotational speed. The traversing arrangement was improved by using stronger gears for traversing motor. The original gears of the machine could not sustain the load of traversing. The traversing motor RPM control was also improved such that the machine would provide a range of traversing speed with respect to the vertical pressure and rotational speed of the tools. The job fixing arrangements were modified to facilitate easy clamping and aligning the jobs as per the traveling line of the traversing tool. The initial job clearance setting with respect to the vertical axis was important to start the welding. The initial clearance between the job and the tool probe was set at 5 mm only. While downing the tool to the plate the touching of the high speed tool and applying pressure produced heavy chatter. The chattering problem was found to be destabilizing the process hence suitable dampers were provided at the foundation of the machine. For this the machine was un-bolted from the foundation and re-bolted.

In addition to this procedure the guide ways of the machine including the traversing guide ways were lubricated and realigned with suitable rigidness to reduce the chattering during welding. The spindle set of the machine was re-hardened to bear the excessive torque. The FSW tool adapter attached to the spindle was specially designed for wear and tear. The spindle bush set was changed to higher quality and alignment of the spindle was also re-checked. The machine was also added an overloading tripper switch to stop the machine in case of overloading of the main motor. This was done to prevent the damage to the main drive motor incase of overloading.

3.3 Trials of Jobs using FSW Tools made of Mild Steels:

FSW is a process which does not require any filler material and is solid state. The FSW tool is the most important part of the process. There is no standardization of the FSW tool in the world. For specific application the tools are to be designed and developed. The tool geometry and the tool material are important for having the required weld characteristics.

The tool material should be such that it can withstand the vertical pressure and torque applied to it. The FSW tool should not wear out easily. The tool shoulder provides the frictional heat to the weld zone of the plates to be welded and the tool pin actually stirs the joint material which leads to the bonding/welding of the plates. Hence choosing the tool material is important for FSW application.

In the present study the tool material initially chosen was mild steel. Mild steel tools were manufactured with the tool probes were given straight cylindrical geometry. The mild steel tool was tried initially for the welding operation. The mild steel FSW tools were more conductive of heat and the tool pin tended to bend during initial application of vertical pressure. The tool only lasted for 3 to 5 jobs and after that the mild steel tools were in-operable. The mild steel tools were observed to be in the range of blue brittleness temperature as the color of the tools changed to bluish as the temperature increased during the welding. Also cracks were found in the periphery of the tool probes. Due to this cracking and bending of the mild steel FSW tools the use of them were discontinued. The FSW welds produced by mild steel tools were not of good quality and generally the tool probe missed the bottom portion of the plates to be joined during stirring operation. This is due to the fact that the tool probe worn out rapidly and hence the length of the tool probe got shortened.

The mild steel FSW tools also were given screwed tool probe geometry. In contrast to the literature, in which the screwed tool probes are better, it was found out the aluminum alloy particles adhered to the screw portion of the mild steel tool probe. Sometimes a layer of material also got adhered to the tool shoulder. This indicated the sticking of the base material to the tool and only after few job the tool became unusable. The mild steel tool probe diameters were kept at 6 mm only. By further increasing the diameter of the probe the plates could not joined. A deep crater was observed for FSW mild steel tools with higher diameter.

3.4 Trials of Jobs using the FSW Tools made of Die Tool Steels:

The FSW tools were also made of die tool steels. Die tools steel is comparatively cheaper and easy to give shape using a CNC machine. There configuration of tool probes were tried. The first was straight cylindrical, second was trapezoidal and third was screwed geometry. The performance of die tool steel was not far superior to mild steel tools. The performance was rather similar to that of mild steel FSW tools. The die steel tools were buckled under vertical loading. The tool was not producing enough heat as the conductivity of the die tool steel was more and hence heat produced during the friction stirring was also getting conducted more. Hence the joints produce were not of good quality. The joint shape was not uniform and often a hole was found out extending the entire length of the weld.

The straight cylindrical tool used was not that successful in initial penetration of the joint plates, hence, the trapezoidal tool was used. The trapezoidal die steel FSW tool was more useful than the straight tool. The screwed tool exhibited similar characteristics of mild steel tool. The tool probe was not strong enough during welding and often the tool went to blue brittleness temperature. The stirring results were not adequate to qualify the weld. The screwed FSW die steel tools were not effective. Just like in case of mild steel FSW tools, the aluminum particles adhered to the screwed surface of the tool and it was unusable after little number of uses. Hence the die steel tools were modified by increasing the diameter of the shoulder and probe to increase heat generation. Even by this also the heat produces was not sufficient to soften the material adequately. The die tool steel tools were expensive as compared to the mild steel tools and not that effective. This indicated the inadequacy of the material. Hence alternative material was searched for the use. The material searched with an intention to increase the frictional heat of the system. Moreover suitable tool geometry was also searched to improve the stirring characteristics of the system.

3.5 Trial of Jobs using Stainless Steel FSW Tool:

After experiencing difficulties in mild steel and die steel FSW tools the attention was focused on stainless steels to produce the welds. Trapezoidal, tapered cylindrical and straight cylindrical tools were designed and tried. The stainless steel was found to be adequate material for FSW operation.

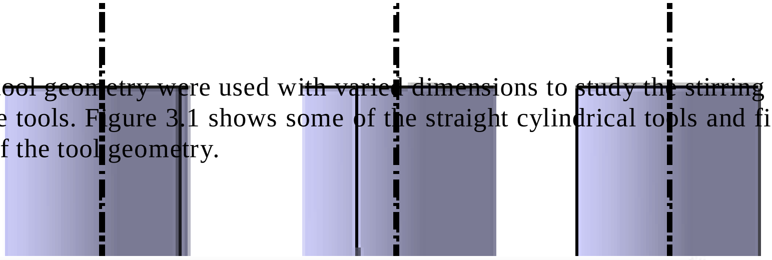
The material selection for the tool is stainless steel having excellent high temperature properties with good ductility and weldability, is designed for high temperature service. It resists oxidation in continuous service at temperatures up to 1150°C. Table 3.1 gives chemical, mechanical and physical properties.

Table 3.1 Properties of steel used as tool

Sl. No.	**Properties**	**Values**
1.	Hardness, Brinell	160
2.	Tensile strength, ultimate (MPa)	655
3.	Tensile strength, yield (MPa)	275
4.	Thermal conductivity at 100 deg C (W/m2 K)	14.2

Figure 3.1: Photographs of some straight cylindrical tools used for the experiments

Three types of tool geometry were used with varied dimensions to study the stirring capability and welding capability of the tools. Figure 3.1 shows some of the straight cylindrical tools and figure 3.2 gives the schematic diagram of the tool geometry.



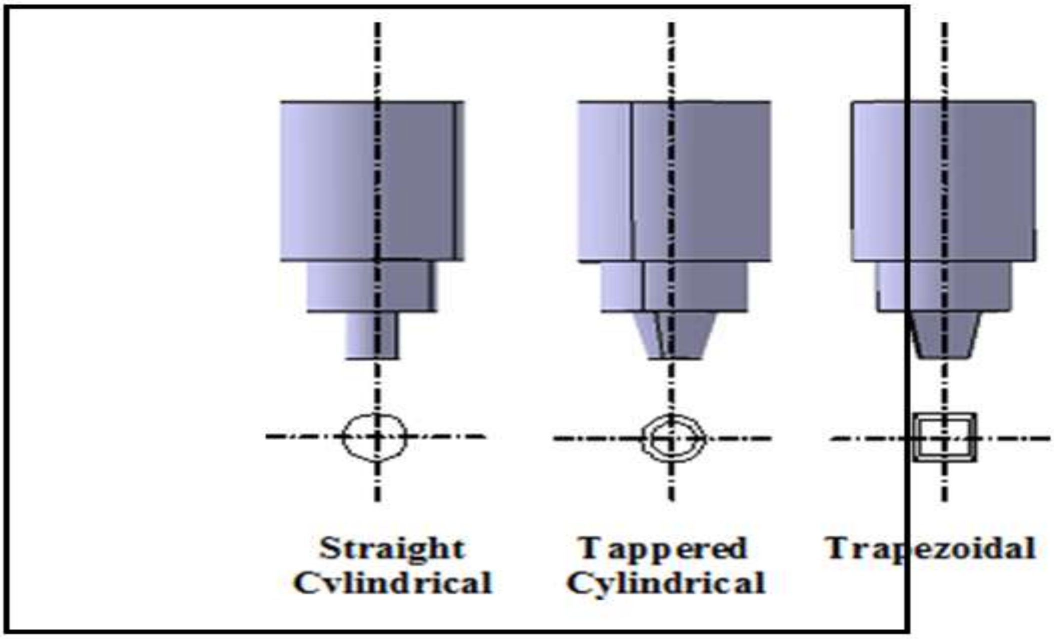


Figure 3.2: CAD drawings of tools being manufactured.

Figure 3.3: Tapered cylindrical tool.

A tapered cylindrical tool is shown in figure 3.3. The tool probes are tapered with different angles to study the probable effects of the tapering of the tool. The tool shoulder diameter and the tapering were done with close tolerance level. The tapering of the tools was done to see the effect of tapering on stirring of the material during welding. It is known that the FSW tool initially penetrates up to the thickness of the plates to be welded. Tapering of the tool probe facilitates easy penetration and lowers the chattering while applying the initial vertical loading.

3.6 Using Proper Process Parameter for Getting the Acceptable Weld:

The use of process parameter is important in any manufacturing process. The FSW process is not yet been standardized hence no proper reference of process parameter was available. It was only known from the literature that the FSW tool rotational speed can be varied from 500 to 3000 RPM. The optimum parameter was to be found out from hit and trial basis. From the preliminary experimental results the rotational speed was fixed at 1400 RPM and the traversing speed was kept at 112 mm/min. The process parameters were kept constant such that the individual effect of the tools on the welds can be studied.

3.7 Testing Samples for Tensile Strength, Grain Structure & Micro-hardness:

The welding capability of the tools and the process was evaluated by studying the tensile strength, microhardness and temperature distributions. The details of these tests are described in this section. The temperature distribution during the FSW is important physical phenomenon. Since the process is not a fusion welding process, it is required that the weld zone temperature should be below the melting temperature of the base metal to be welded yet should be high enough to raise the temperature up to semisolid state. The FSW weld material should be elevated to a temperature such that the material should be in semisolid paste like state. The semisolid state of the material softens the material and facilitates easy stirring.

Figure 3.4: Aluminum Plates with Thermocouples.

If the temperature of the material is not up to the requirement then bonding might not occur. It is also thought that the tool geometry has some effect on the peak temperature distributions of the FSW welds. The tool geometry effects on the temperature distributions were experimentally determined using temperature recording set up. The temperatures at 20 mm away from the weld line were measured using data logger and K-type Chromel-Alumen thermocouples. In figure 3.4 the attachments of thermocouples with the plates are shown. The plates were welded attached with the thermocouples and the temperature profiles for each tool was recorded. A FSW joint is shown in figure 3.5, which shows the plates, weld and the smooth finish due to the FSW.

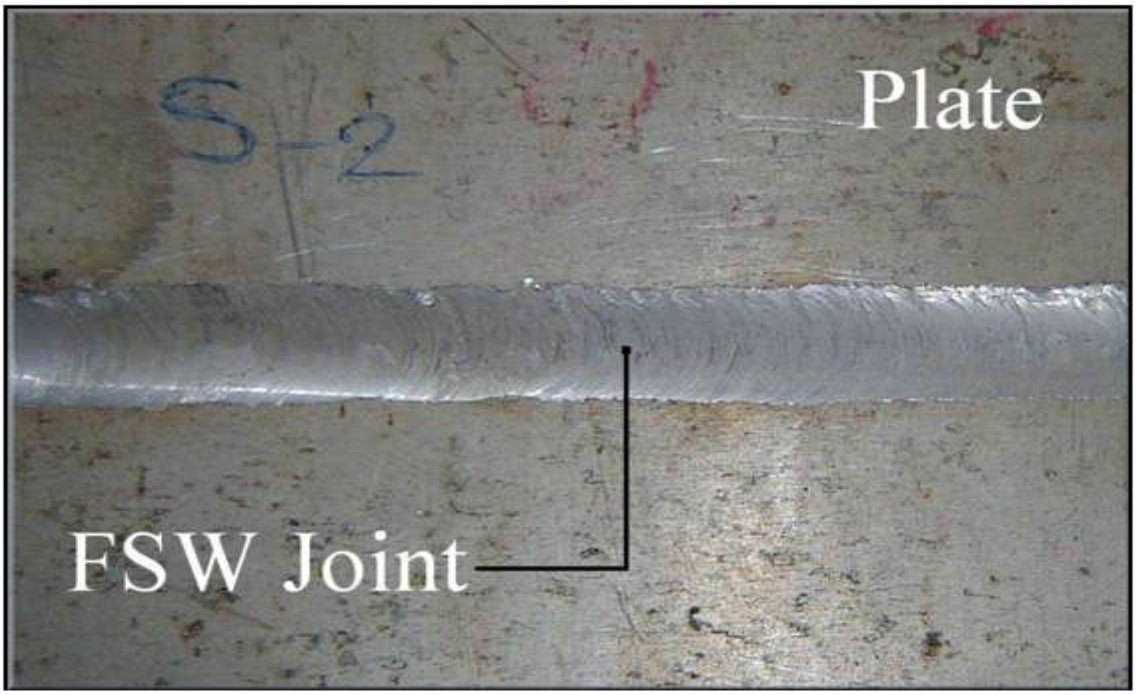


Figure 3.5: FSW Joint of Aluminum Plates.

The FSW tools and process parameters were evaluated by testing the weld samples. It is known that during the FSW process certain degree of stirring takes place in the weld zone and thus grain refinement in the weld zone is expected. However the tensile testing is required to ascertain any loss of ductility that might happen to the weld due to the process. During the present investigation the FSW tool samples were cut and tensile tested to check the ductility characteristics of the joints. The FSW welds were cut according to the ASTM specifications for tensile testing. In figure 3.6 the tensile specimens prepared from the FSW samples are shown. Each sample was cut for preparing the tensile testing specimen.

Figure 3.6: Tensile specimens of FSW Joints.

The tensile testing sample preparation details are shown in figure 3.7. To have the tensile specimen ready the FSW plates were initially cut by marking the plates according to the procedures given in the literature. The specimens were initially prepared in rectangular fashion. The final shapes of the tensile specimen with desired gauge radius were incorporated afterwards. The specimens were rechecked for smoothness of the surface to avoid any stress raisers like notches or scratches.

Figure 3.7: Tensile specimens of FSW Joints preparation.

The tested tensile samples are shown in figure 3.8. The various samples which were broken are indicated in the figures. Each sample represents a separate tool but with same process parameter. This was done to study the effect of tool geometry on the weld tensile property.

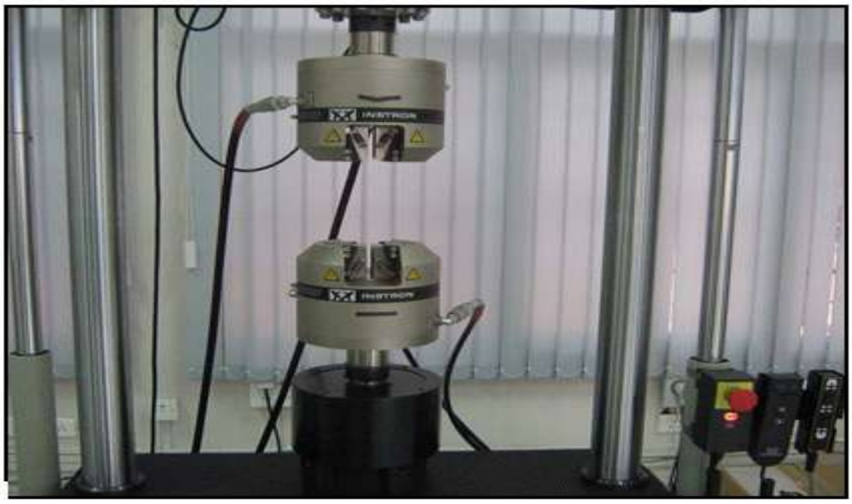


Figure 3.8: Tensile testing of FSW Joints.

Figure 3.9: Close-up view of tensile testing of FSW Joints.

Figure 3.10: Some of the tested tensile specimens of FSW Joints.

The tensile testing of the welds was done using a computerized UTM machine at IIT, Kharagpur. The UTM machine used is completely computerized and calculates the load verses displacement of the experiments and presents the output in computerized form to be used in the spreadsheets. The UTM machine used and the close-up view of the experimental setup are shown in figures 3.9 & 3.10 respectively.

The welded samples were also tested for metallographic features. The micro-hardness and the grain size of the welded samples were measured. The metallographic instrument used for the experiments is shown in the figure 3.11.

Figure 3.11: Metallographic testing of FSW joints.

The microhardness of the FSW samples was measured using a computerized microhardness tester. The photograph of the machine with a weld sample is shown in figure 3.12. The hardness was tested by the depression of the diamond on the microstructure. The enlarged view of this diamond indentation is shown in figure 3.12. Each weld was tested for the microhardness. The microhardness of the weld zone and the heat affected zones were measured for each type of tool for each sample. The enlarged view of diamond indentation and its computerized photographs are shown in figure 3.13.

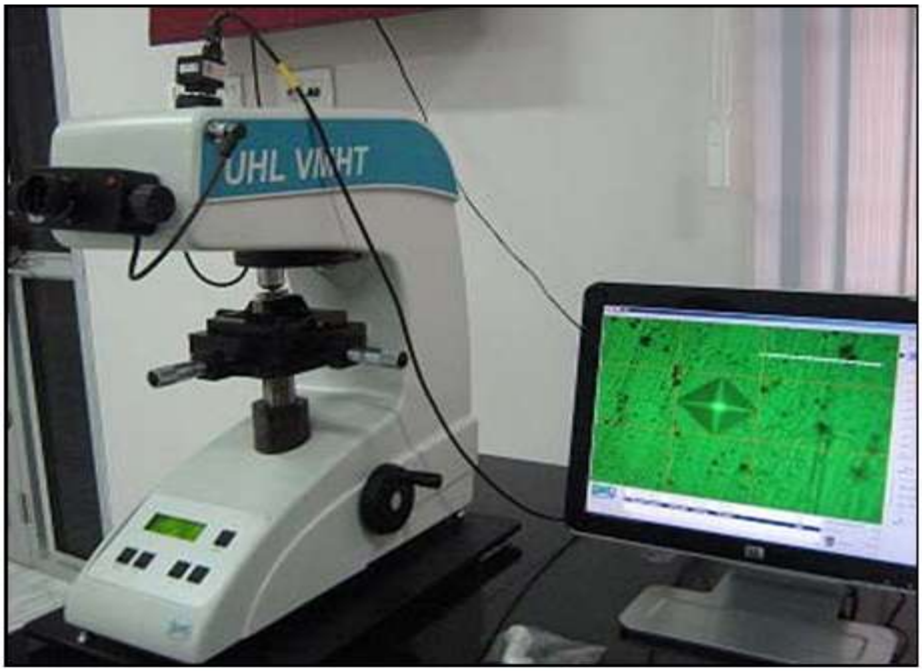


Figure 3.12: Metallographic (hardness) testing of FSW joints.

Figure 3.13: Diamond indenting testing of FSW joints

Figure 3.14 shows the FSW process in progress. The complete setup is shown with FSW tool, temperature measurement probe, clamping and the completed weld. It can be observed from the figure that unlike fusion welded structure there is no ripple effects and the weld is quite smooth achieved without any use of filler material.

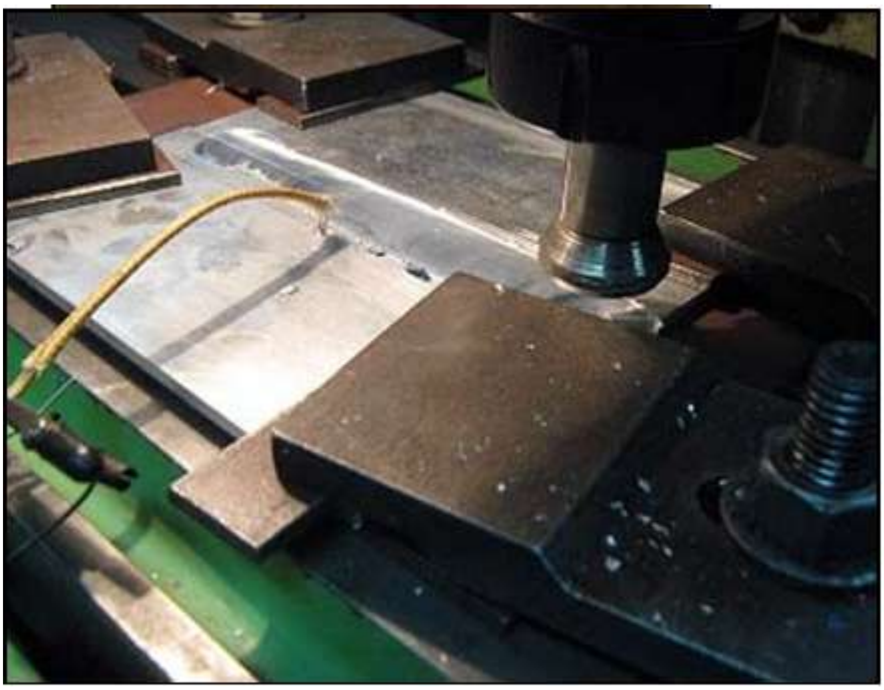


Figure 3.14: FSW of aluminum plate in progress.

Figure 3.15: Trial FSW of aluminum plates.

Figure 3.16: FSW of aluminum joint.

Figure 3.17: FSW of aluminum joint end portion.

A completed FSW welded joint with thermocouple attached to it is shown in figure 3.15. Another completed FSW joint is shown in the figure 3.16. A close up view of the weld with the starting mark is shown in figure 3.17. The FSW tools used in the present investigation were evaluated with respect to the tensile strength, macrohardness and grain size of the weld and heat affected zone. These results are discussed in the next section. From the experimental investigation it was observed that the process developed is quite stabilized one and inherently possesses many merits as compared to fusion welding of aluminum alloys.

III. Chapter – Iv Results And Discussion

RESULTS AND DISCUSSIONS

The FS welds were sectioned and tested for studying the joint strength, micro-hardness and grain size. The effect of tool geometry on the temperature was also studied. In the following sections the results are discussed. The results are not quantitatively much different from one another, though variation in respect to grain size and variation with respect to tensile strength was observed.

The visual inspection of eight tools provided the soundness of the welding. The weld zone was smooth without any ripple effects. No blind hoe was found out in the sectioned samples. Figures 4.1 (a) & (b) show the overall view of the weld when photographed.

Figure 4.1(a): Close-up view of a weld.

Figure 4.1(b): Close-up view of a weld.

The visual inspection indicated that the welds are sound enough appearance wise. The welds were cross sectioned to observe any possible blind holes that are reported in the literature for faulty FS welding. No such holes were found out. This indicated the soundness of the welds and further study was needed to establish the process.

The cross sectioned samples were machined as per the ASTM standards for tensile testing. The machining was done using a milling machine. The gauge radiuses of the samples were as per the specifications given in the literature. The samples were smooth finished during machining. This was done to avoid any notch or any stress raiser. In aluminum alloy even the machining marks can act like a stress raiser. The machining parameters were set in such a way that no visible machining marks were present in the samples.

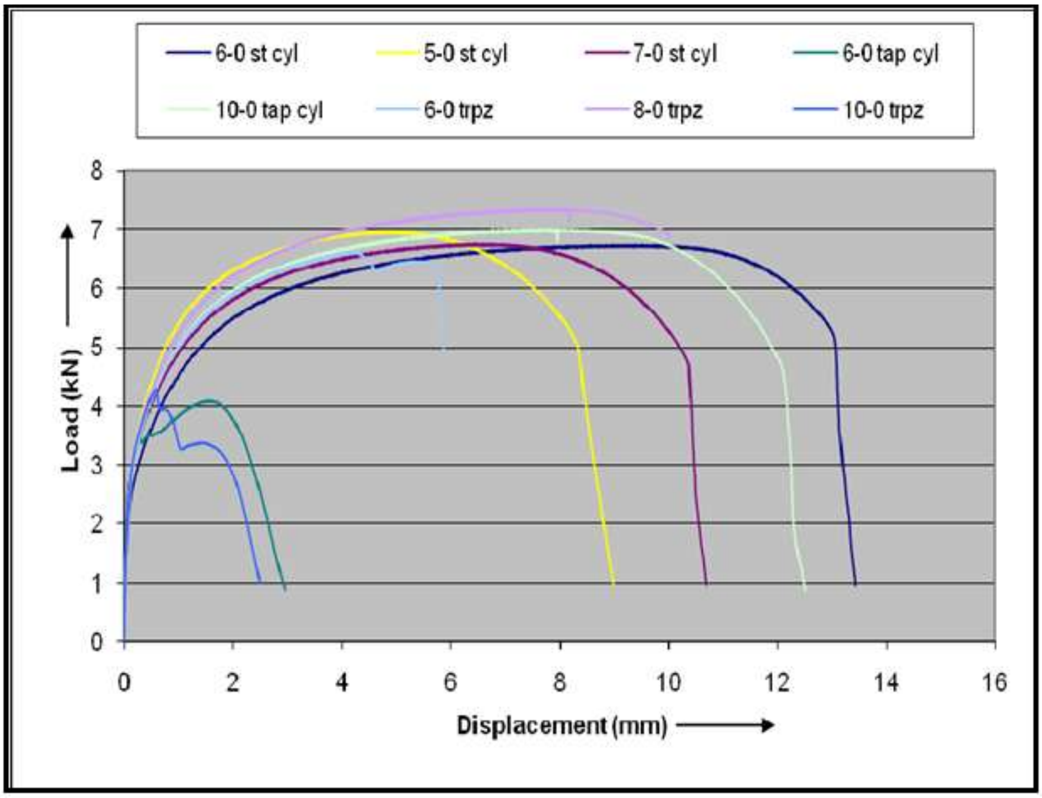


Figure 4.2: Tesnsile testing results of the FSW tools.

The tesnile testing of all the tools were conducted and the tensile testing data is plotted in figure 4.2. The tensile testing results show that except for 10 mm thick trapezoidal tool the tensile proprty of the weld improved considerabley.

The experimental temperature distributions 20 mm away from the weldline for all the tools are shown in figure 4.4. It can be observed that there is some variation of temperature distribution between the tools. The highest temperature is observed for straight cylindrical tool with 6 mm probe diameter. The next highest was for 10 mm probe diameter based trapezoidal tool.

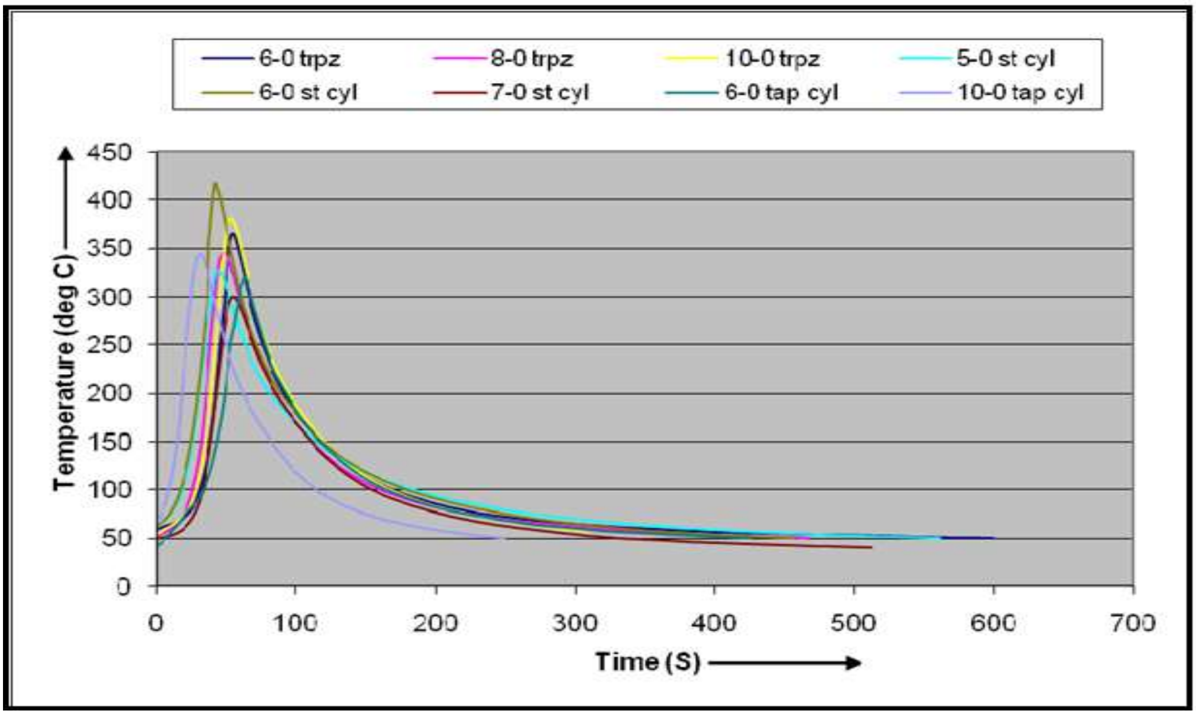


Figure 4.3: Temperature distribtuion results.

The micro-hardness of the samples is shown in the figure 4.4. It can be observed that there is no appreciable change in the hardness of the weld zones with respect to the tool geometry. It is observed from the graph that the hardness values of the weld zone and the nuggets are lower than the base materials. This indicates the improved ductility of the weld. In almost all the cases the hardness value remained almost same for weld zone and heat affected zone (HAZ). In the case of 5mm diameter based straight cylindrical tool the hardness slightly increased for the weld zone. Still, it is well below the hardness value of the base metal. This is indicative of FSW phenomenon that the ductility of the weld improves in comparison to the base material.

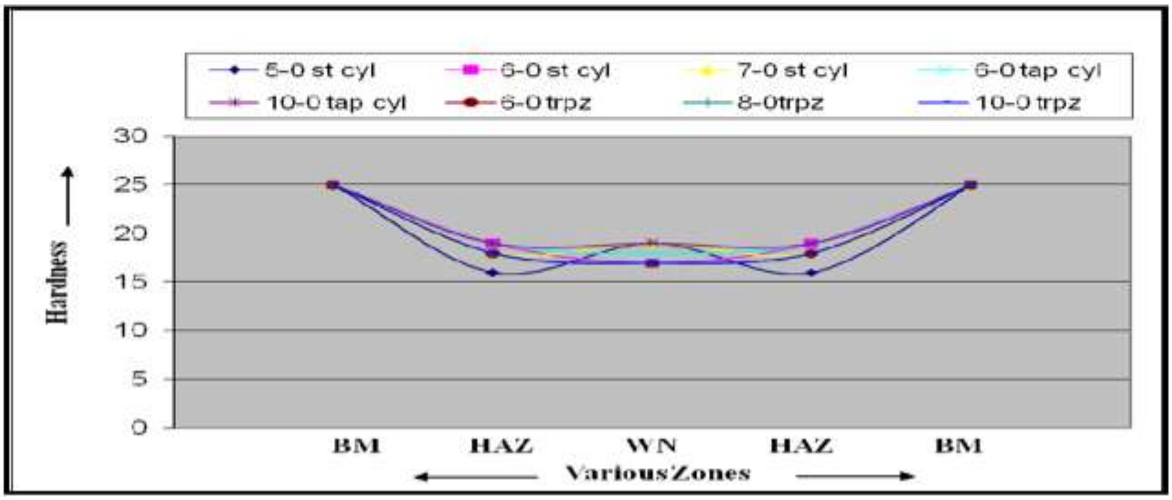


Figure 4.4: Micro-hardness of the FS weld samples.

The welds were also tested for the grain size measurement. The micrographs were taken and average grain sizes were measured. In the figures below some of the microstructures of the weld zones and HAZ are shown. Figures 4.5 & 4.6 shows the microstructures of weld HAZ for 5 & 6 mm diameter cylindrical tools respectively. Figure 4.7 shows the microstructures of weld HAZ for 10 mm probe diameter tapered cylindrical tool, whereas, figure 4.8 shows the microstructures of weld HAZ 10 mm probe diameter trapezoidal tool. It can be observed that there is no formation of grain coarsening, which occurs in fusion welded HAZ indicative of soundness of the weld. Figure 4.9 shows the weld zone microstructure for 6 mm tapered probe tool and the weld zone microstructure for 10 mm trapezoidal tool is shown in figure 4.10.

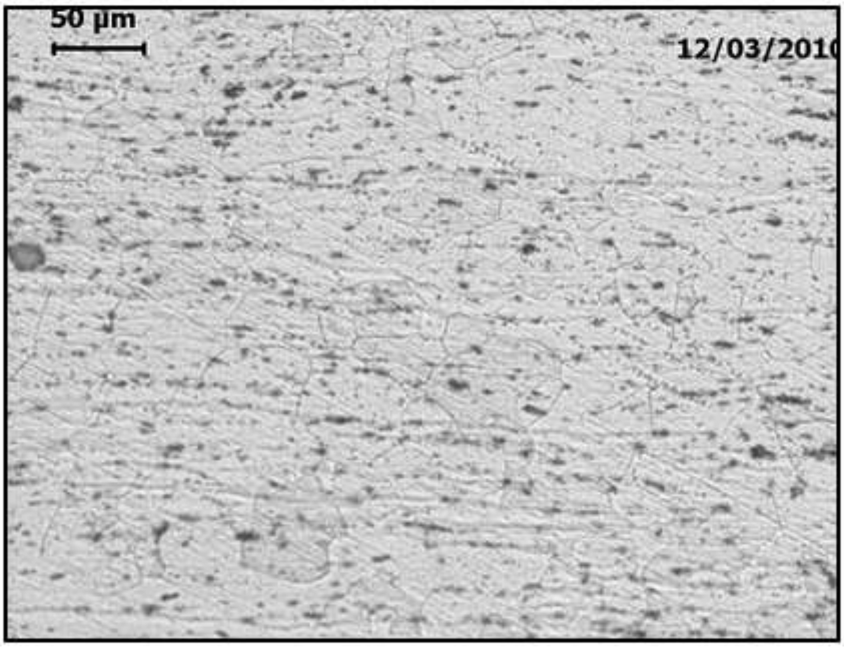


Figure 4.5: HAZ microstructure for 5 mm probe diameter cylindrical tool.

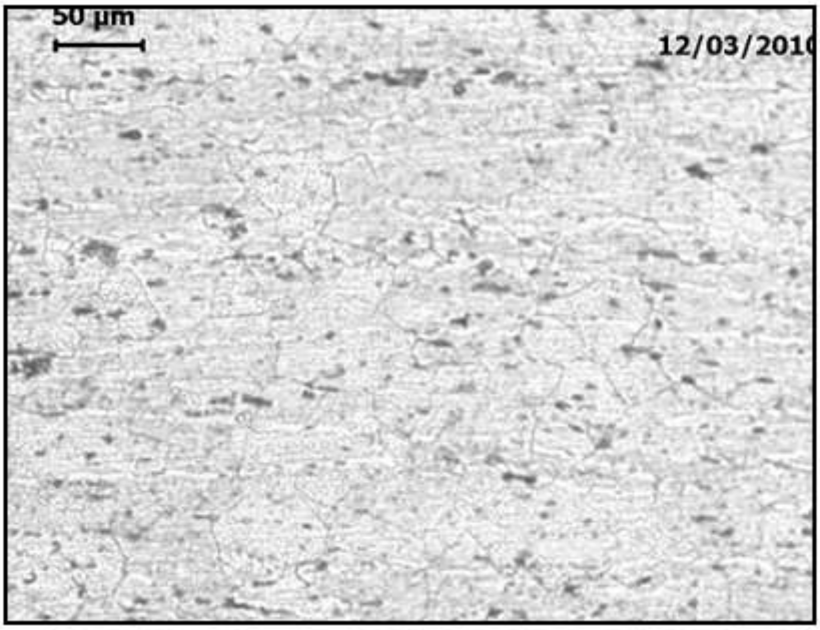


Figure 4.6: HAZ microstructure for 6 mm probe diameter cylindrical tool.

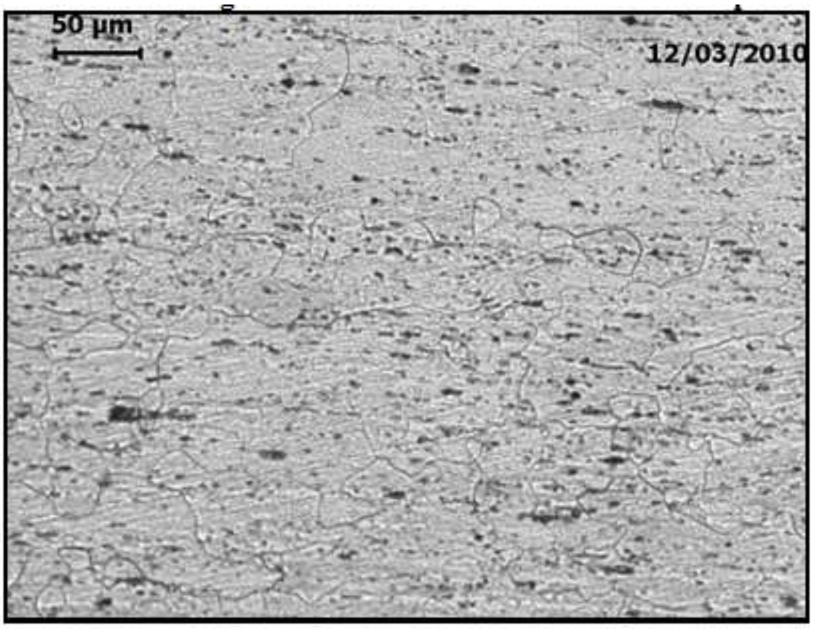


Figure 4.7: HAZ microstructure for 10 mm probe diameter tapered cylindrical tool.

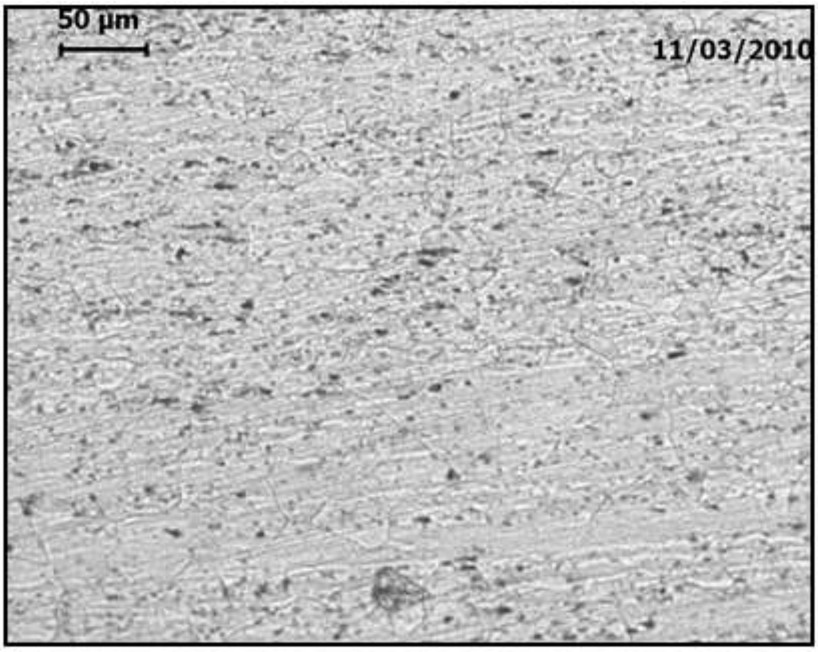


Figure 4.8: HAZ microstructure of 10 mm probe diameter trapezoidal tool.

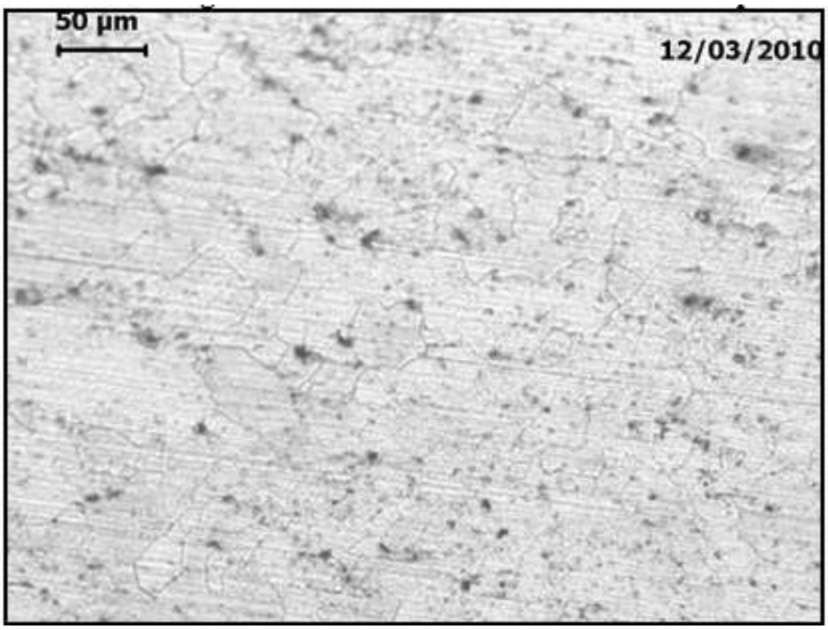


Figure 4.9: Weld zone microstructure for 6 mm probe diameter tapered tool.

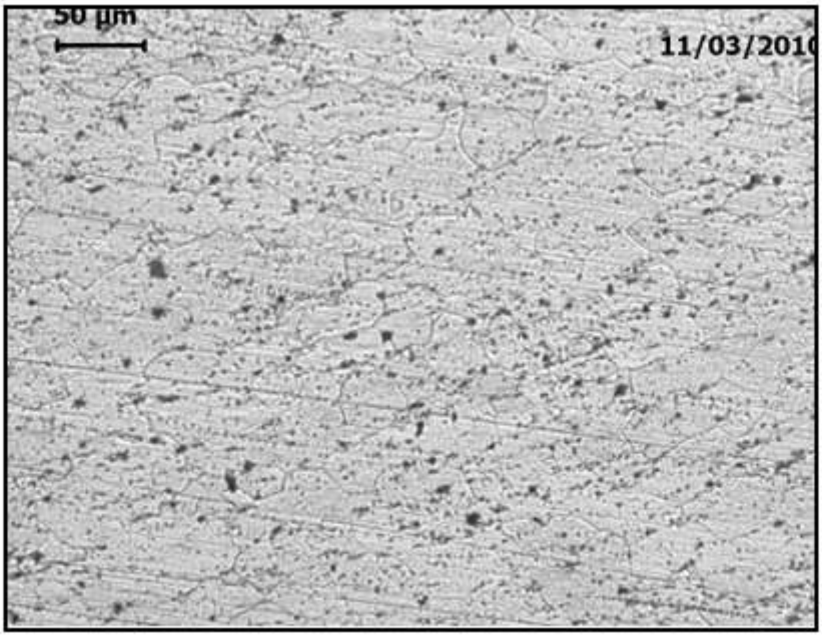


Figure 4.10: Weld zone microstructure for 10 mm probe diameter trapezoidal tool.

The grain size obtained from these micrographs is shown in table 4.1. From the table, it can be observed that the weld zone is stirred and having more grain refinement as compared to the HAZ zone. For every type of tool used the weld zone showed better refinement as compared to the HAZ.

Table 4.1 Average grain size of weld and HAZ.

Sl. No.	**Samples**	**Average Grain Size (microns)**
(a). HAZ		
1	HAZ_5-0_st_cyl	41.61
2	HAZ_6-0_St_cyl	47.93
3	HAZ_6-0_tap_cyl	48.08

4	HAZ_6-0_trpz	45.52
5	HAZ_7-0_st_cyl	35.03
6	HAZ_8-0_trpz	32.66
7	HAZ_10-0_tap_cyl	62.04
8	HAZ_10-0_trpz	46.42
(b). WELD ZONE		
9	WZ_5-0_st_cyl	33.67
10	WZ_6-0_St_cyl	30.41
11	WZ_6-0_tap_cyl	37.62
12	WZ_6-0_trpz	34.89
13	WZ_7-0_st_cyl	39.03
14	WZ_8-0_trpz	33.29
15	WZ_10-0_tap_cyl	33.83
16	WZ_10-0_trpz	41.35

IV. Chapter – V Conclusion

CHAPTER - V
CONCLUSION

Developing a tool for Friction Stir welding with its all geometric parameters is the major concern for obtaining satisfactory weld for 6 mm thick aluminum alloy plate. Design of tool pin profile and setting the welding parameters (tool rotational speed and tool travel speed) are the two most important factors while implementing the process from the production point of view.

From the preceding investigation the following conclusions can be drawn:

In this project a number of Friction Stir Welding tools of stainless steel have been successfully developed to carry out the welding operation. Basically three types of tools has been used which are straight cylindrical, tapered cylindrical and trapezoidal. The tensile testing results show that except for 10 mm diameter tappered cylindrical tool the tensile proprty of the weld improved considerably. The highest temperature is observed for straight cylindrical tool with 6 mm probe diameter. The next highest was for 10 mm probe diameter based trapezoidal tool. There is no appreciable change in the hardness of the weld zones with respect to the tool geometry. It is observed that the hardness values of the weld zone and the nuggets are lower than the base material which indicates the improved ductility of the weld. In almost all the cases the hardness value remained almost same for weld zone (WZ) and heat affected zone (HAZ). In the case of 5mm diameter straight cylindrical tool the hardness slightly increased for the weld zone. From the micro-structural study it has been observed that the weld zone is stirred and having more grain refinement as compared to the HAZ zone. The present investigation indicates that the tools and the process developed are quite suitable for commercial applications. The weld strength and quality of the weld obtained during the experiment indicated the success of the process.

V. Scope For Future Work

Since the time of invention a great deal of progress has been made in implementing Friction Stir Welding in production of aluminum structures. This process is most suitable for components which are flat and long (plates and sheets) but can be adapted for pipes, hollow sections and positional welding. Initially developed for non-ferrous materials such as aluminum, by using suitable tool materials the use of the process has been extended to harder and higher melting point materials such as steels, titanium alloys and copper.

REFERENCES

[1]. **Wang Dequing, Liu Shuhua**, "Study of Friction stir welding of aluminum", Journal of Materials Science Volume 39 (2004) 1689 – 1693

[2]. **Scialpi, L.A.C. De Filippis, P. Cavaliere,** "Influence of shoulder geometry on microstructure and mechanical properties of friction stir welded 6082 aluminum alloy", Journals for Materials and Design, Volume 28 (2007) 1124-1129 DOI:10.1016/j.matdes.2006.01.031.

[3]. **Hidetoshi Fujii, Ling Cui, Masakatsu Maeda, Kiyoshi Nogi,** "Effect of tool shape on mechanical properties and microstructure of friction stir welded aluminum alloys ", Journal of Material Science and Engineering, Volume A 419 (2006),Pages 25-31.

[4]. **Mustafa Boz, Adem Kurt,** "The Influence of Stirrer Geometry on Bonding and Mechanical Properties in friction stir welding process", Journal of Materials and Design, Volume 25 (2004), Pages 343-347.

[5]. **M. Cabibbo, H.J. McQueenb, E. Evangelista, S. Spigarelli, M. Di Paola, A. Falchero,** "Microstructure and mechanical property studies of AA6056 friction stir welded plate", Journal of Materials Science and Engineering, Volume A 460- 461 (2007), Pages 86-94.

[6]. **Furkan Sarsilmaz – Ulas caydas,** "Statistical Analysis on Mechanical Properties of Friction Stir Welded AA1050/AA5083 couples", International Journal of Advanced Manufacturing Technology (2008), DOI 0.1007/s00170-008-1716-x.

[7]. **T Sakthivel, G S Senegar, J Mukhopadhyay,** "Effect of Welding Speed on Micro-structure and Mechanical Properties of Friction-stir Welded Aluminum", International Journal of Advanced Manufacturing Technology (2008), DOI 10.1007/s00170-008-1727-7.

[8]. **J. Adamowski, M Szkodo,** " Friction-stir-welds (FSW) of Aluminum alloy AW6082-T6 ", Journal of Achievements in materials and Manufacturing Engineering, Volume 20, Issue 1-2, January-February 2007.

[9]. D M Rodrigues, A Loureiro, C Leitao, R M Leal, B M Chaparro, P Vilaca, "Influence of Friction Stir Welding Parameters on the Micro-structural and Mechanical properties of AA 6016-T4 Thin Welds", Journals for Materials and Design (2008), DOI 10.1016/j.matdes.2008.09.016.

[10]. **Y.G. Kim a, H. Fujii, T. Tsumura, T. Komazaki, K. Nakata,** "Effect of Welding Parameters on Microstructure in the Stir Zone of FSW Joints of Aluminum die Casting Alloy ", Journals for Materials Letters Volume 60 (2006) 3830–3837 DOI:10.1016/j.matlet.2006.03.123.

[11]. **Yutaka S Sato and Hiroyuki Kokawa,** "Distribution of Tensile Property and Micro-structure in Friction stir Weld of 6063 Aluminum", Metallurgical and Materials Transactions, Volume 32A, December 2001-3023.

[12]. **C Yeni, S sayer, O Ertugrul, M Pakdil,** "Effect of Post Weld-aging on the Mechanical and Micro-structural Properties of Friction-stir Welded Aluminum alloy 7075", Achieves of Material Science and Engineering, Volume 34, Issue 2, December 2008, Pages 105-109.

[13]. **C G Rhodes, M W Mahoney, W H Bingel, M Calabrese,** "Fine-grain Evolution in Friction-stir Processed 7050 Aluminum", Elsevier Science Ltd. (2003), Doi:10.1016/S1359-6462(03)00082-4.

[14]. **M B Durdanovic, M M Mijajloric, D S Milcic, D S Stamenkovic,** "Heat Generation during Friction-stir-welding (FSW) process", Tribology in Industry, Volume 31, No. 1 & 2, 2009.

[15]. **Yeong-Maw Hwang, Zong-Wei Kang, Yuang-Cherng Chiou, Hung-Hsiou Hsu,** "Experimental study on temperature distributions within the workpiece during friction stir welding of aluminum alloys", International Journal of Machine Tools & Manufacture, Volume 48 (2008) 778–787.

[16]. **R.W. Fonda, J.A. Wert, A.P. Reynolds and W. Tang,** "Initial Microstructural Evolution during Friction Stir Welding", Material Science and Technology 2007 175-177.

[17]. **T R McNelley, S Swaminathan and J Q Su,** "Recrystallization mechanisms during friction stir welding/processing of aluminum alloys", Elsevier Science Ltd. (2007), Doi:10.1016/ j.scriptamat.2007.09.064.

[18]. **E. Cerri , P. Leo,** "Warm and room temperature deformation of friction stir welded thin aluminum sheets", Journals for Materials and Design (2009) Volume 31 1392-1402.

[19]. **Yutaka S Sato, Hiroyuki Kokawa, keiske Ikeda, Masatoshi Enomoto, Shigetoshi Jogan and Takenori Hashimoto,** "Microtexture in the Friction stir Weld of Aluminum Alloy", Metallurgical and Materials Transactions, Volume 32A, April 2001 941-948.

[20]. **Z Y Ma,** "Friction Stir Processing Technology: A Review", Metallurgical and Materials Transactions, Volume 39A, March 2008 642-658.

[21]. **H.K.D.H. Bhadesia and T. DebRoy,** "Critical Assessment: Friction Stir Welding of Steels", Science and Technology of Welding and joining, 2009. Volume 14 No:3194.

[22]. **T. J. Lienert, W. L. Stellwag, JR., B. B. Grimmett & R. W. Warke,** "Friction Stir Welding Studies on Mild Steel", The Welding Journal, January 2003.

[23]. **R.W. Fonda and J.F. Bingert,** "Micro-structural Evolution in the Heat-Affected Zone of a Friction Stir Weld", Metallurgical and Materials Transactions, Volume 35A, May 2004-1487.

[24]. **Moataz M. Attallah, Claire L. Davis and Martin Strangwood, "**Microstructure-microhardness relationships in friction stir welded AA5251", Journal of Material Science (2007) 42:7299–7306 DOI 10.1007/s10853-007- 1585-y.

[25]. **Zhaoxin Meng, Hui Chen and Xihua Yue,** "Study on Optimization of Stir Head for FSW based on Genetic Algorithm", International Federation for Information Processing (IFIP), Volume 207, 483-491.

[26]. **E. Sukedai, T. Maebara and T. Yokayama,** "Micro-structure analysis of a friction-stir welded 2024 aluminium alloy using electron microscopy", EMC 2008, Vol. 2: Materials Science, pp. 673–674, DOI: 10.1007/978-3-540-85226-1- 337.

Dr Himanshu Sekhar Moharana " Studying the Effect of Tool Geometries on Friction Stir Welds" International Journal of Engineering Science Invention (IJESI), Vol. 04, No. 06, 2015, PP 81-105.