CHAPTER 3

EXPERIMENTAL WORK

3.1 INTRODUCTION

The fascination exerted by aluminum at this time is well illustrated by a quote of Jules Verne taken from "From the Earth to the Moon" (1865) [132]: "This valuable metal (aluminum) possesses the whiteness of silver, the indestructibility of gold, the tenacity of iron, the fusibility of copper, the lightness of glass. It is easily wrought, is very widely distributed, forming the base of most of the rocks, is three times lighter than iron, and seems to have been created for the express purpose of furnishing us with the material for our projectile." Indeed, aluminum has a remarkable combination of qualities that includes low density (one-third the density of steel), high ductility, high thermal and electrical conductivity, good corrosion resistance, attractive appearance and non-toxicity.

The use has grown up steadily in various applications like aerospace, marine, transport and automotive industries which were expected since long. Hence the material focused in this thesis is aluminium alloys, a material of future.

The purpose of the research was to develop the basic understanding of friction stir welding process; and to determine and optimize the process variables for joining 6xxx Aluminum-Magnesium-Silicon Alloys. The investigation was focused on straight butt weld configurations using conventional as well as fixed gap bobbin tool. The welding was done perpendicular to the rolling direction. The welding was performed using conventional milling machine and CNC milling machine (VMC).

3.1.1 6xxx, Aluminum-Magnesium-Silicon Alloys

The major characteristics of the 6xxx series are:

The 6xxx alloys are heat treatable and have moderately high strength coupled with excellent corrosion resistance. A unique feature is their great extrudability, making it possible to produce in single shapes relatively complex architectural forms, as well as to design shapes that put the majority of the metal where it will most efficiently carry the highest tensile and compressive stresses. This feature is an important advantage for architectural and structural members where stiffness criticality is important.

3.2 SELECTION OF WORK MATERIAL

From the literature it was observed that different types and grades of Al alloys were studied by number of researchers in the category of non-heat treatable and heat treatable alloys. Out of total list in the group of 6xxx series AA 6101 T6 alloy was not explored much for FSW and hence it was selected as a work material under consideration. The second material selected was AA 6082 T6, a newly developed alloy again in the same series but having a bright future due to its strength and other advantages compatible with steel. Chemical compositions and material properties are shown in Table 3.1 and 3.2 respectively.

3.2.1 AA6101 Alloy Specification

AA 6101 is best suited for applications involving moderate strength and maximum electrical conductivity. It is similar to alloy 6063, but with minor chemistry changes which enhance electrical conductivity. Although slightly lower in conductivity than alloy 1350, it offers greater strength. Its most typical application is in bus bar and light structural applications ranging from ladders and yacht masts to automotive and rail car sections [133].

3.2.2 AA 6082 Alloy Specifications

Aluminium alloy AA 6082 also corresponds to the following standard designations and specification: AA6082, HE30, ENAW-6082, ISO AlSi1MgMn, A96082 Aluminium alloy. 6082 is a medium strength alloy with excellent corrosion resistance. It has the highest strength of the 6000 series alloys. Alloy 6082 is known as a structural alloy. As a relatively new alloy, the higher strength of 6082 has seen it replace 6061 in many applications. The addition of a large amount of manganese controls the grain structure which in turn results in a stronger alloy.

The higher strength alloys (6061, 6261, 6351 and 6082) are used in diverse applications including automotive components, bus and truck chassis and body sections, and marine structural sections especially in high speed catamarans [133]. It is typically used in highly stressed applications, Trusses, Bridges, Cranes, etc.

Table 3.1: Chemical compositions of the materials selected [134]

	AA 6101 T6, H9	AA6082 T6, HE30
Component	Wt. %	Wt. %
Si	0.3 - 0.7	0.7 - 1.3
Mg	0.35 - 0.7	0.6 - 1.2
Mn	0.03 max	0.4 - 1
Fe	0.5 max	0.5 max
Cr	0.03 max	0.25 max
Zn	0.1 max	0.2 max
Other, total	0.1 max	0.15 max
Ti	--	0.1 max
Cu	0.1 max	0.1 max
Other, each	0.03 max	0.05 max
Al	remainder	95.2 - 98.3
Boron	0.06 max	--

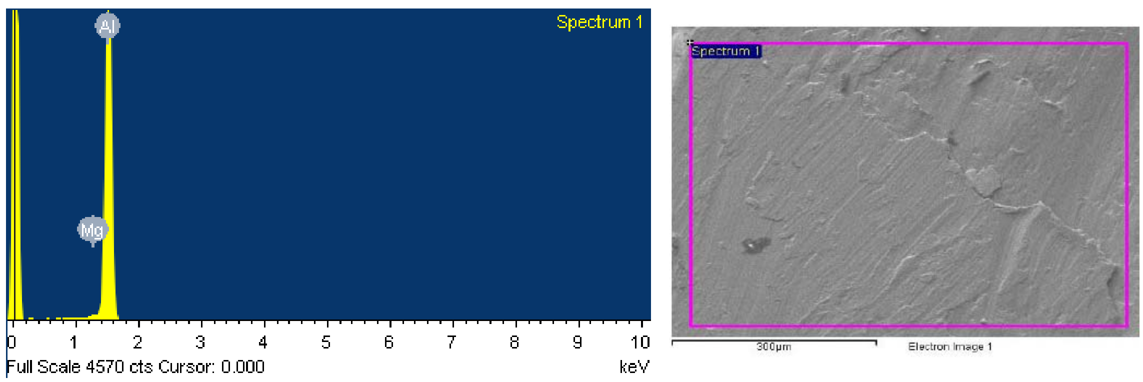
Table- 3.2: Properties of AA 6101 and 6082 Al alloy [134][135]

	AA 6101 T6	AA6082 T6
Property	Value in metric unit	Value in metric unit
Density	2.70 g/cc	2.7 g/cc
Modulus of elasticity	69 GPa	70 GPa
Thermal conductivity	220 W/(m*K)	170 W/m-K
Electrical resistivity	2.80×10^{-8} Ohm*m	0.038 x10-6 Ω .m
Tensile strength (T6)	221 MPa	310 MPa
Yield strength (T6)	193 MPa	260 MPa
Elongation (T6)	15 %	10 %
Hardness (T6)	71 HB	95 HV
Melting point	660 °C	555 °C

3.2.3 EDS Analysis of Raw Material Used In the Experiment

Table 3.3: Composition of AA 6101 T6 Alloy

Element	Si	Fe	Mn	Mg	Al
Weight %	0.31	0.16	0.06	0.46	98.97



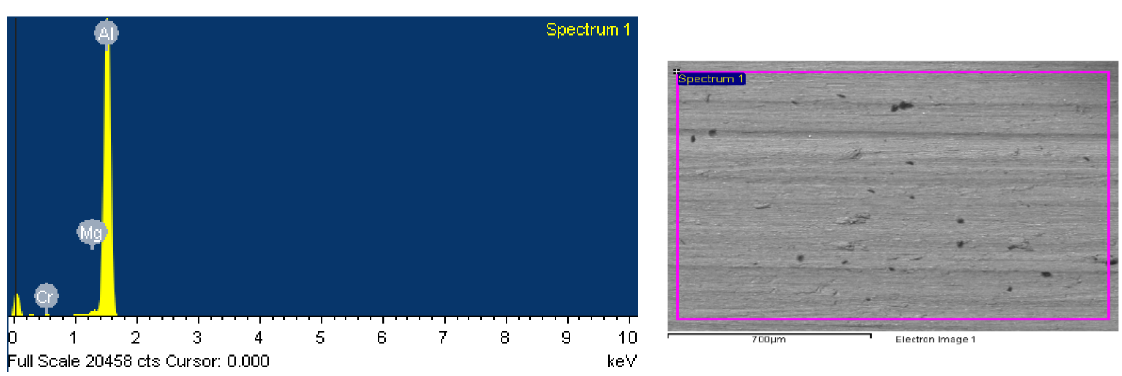
(a) (b)

Figure 3.1: Analysis of AA 6101 T6 Alloy (a) EDS Curve for AA 6101 T6 Alloy

(a) Image for Base metal

Table 3.4: Composition of AA 6082 T6 Alloy

Element	Si	Fe	Cu	Mn	Mg	Cr	Al
Weight %	0.88	0.45	0.04	0.43	1.05	0.11	97.03



(a) (b)

Figure 3.2: Analysis of AA 6082 T6 Alloy (a) EDS Curve for AA 6082 T6 Alloy

(a) Image for Base metal

3.3 INITIAL EXPERIMENTAL APPROACH

The purpose of the investigation was to determine factors affecting weld quality and to determine their causal relationships. This required a more explorative approach compared to the design of experiment (DOE) method.

The area of specific interest was how the tool features and process variables (speed, feed) interacted. There was a need to develop in house setup for friction stir welding. It was a need to have hands on experience to get basic process understanding. So a conventional milling machine was procured to serve the purpose.

The basic understanding was built based on the literature about single shoulder tools. Initial approach was to develop different tools for single shoulder FSW. Also clamping device need to be developed for proper work fixation and rigid support.

3.4 RESEARCH APPROACH: ADAPTED

From the literature it was observed that there are several variables like, process variables (e.g. tool rotational speed, traversing speed), tool design features (tool shoulder and probe features), tool dimensions (shoulder and pin). The tests to be performed (e.g. mechanical and microstructure, corrosion etc.) to know effects of above parameters on weld quality. This will result into wide range of experimentation.

Another observation was the material selected for the tool. Cost of tool is a limiting factor in FSW. So the intension was focused to develop economical designs and select the affordable tool material. It was then extended to the development of bobbin friction stir welding (BFSW).

Insights gained and intuition used to create a conceptual design of tools and fixtures to be used in the experimental work for both CFSW and BFSW. The different parts of this approach are elaborated below.

3.5 HARDWARE DEVELOPMENT

3.5.1 Design and Development of Mechanical Fixture

Fixturing for friction stir welding usually is the most complicated and critical aspect of the process. The workpieces must be clamped to a rigid backing plate (anvil) and secured to resist the perpendicular and side forces that develop during welding. These forces tend to lift and push the workpieces apart. Fixtures are designed to restrain the workpieces and keep them from moving. A root opening (gap) of less than 10% of the material thickness can be tolerated for thicknesses up to about 13 mm (1/2 in.). The fixtures that hold the materials to the backing plate should be placed as close to the joint as possible to reduce the clamping load.

The main purpose of a fixture for friction stir welding is to hold the work-pieces in position during welding. However, there is limited published information available which will highlight the fixture design. The main reason for having appropriate clamps or fixtures is to prevent the work piece from moving while being welded. Obtaining good stability and rigidity during the process is important since any deflection or major vibration would affect the quality of the weld.

3.5.2 Conceptual thinking

Only clamping the work piece is not the criteria in FSW but restriction of movements and flexibility in clamping is more important. It is observed that using a milling vice (Figure 3.3) for clamping the object can easily be used, but to do the research work, one has to experiment as per standards developed previously, and for that, such vice will not serve the purpose. If we clamp using these vice then there are maximum chances of lifting off the substrate from the center. So an understanding is required to be developed for proper clamping of the work piece (plates) to be butt welded.

Figure 3.3: Different types of vice used in conventional machining process.

As suggested by TWI, the inventor, that (i) a rigid clamping is required to get quality weld and to avoid accident during friction stir welding (ii) a backing plate is required which will provide strong support sufficient enough to limit bending of substrate (iii) horizontal and vertical plate movement should be restricted.

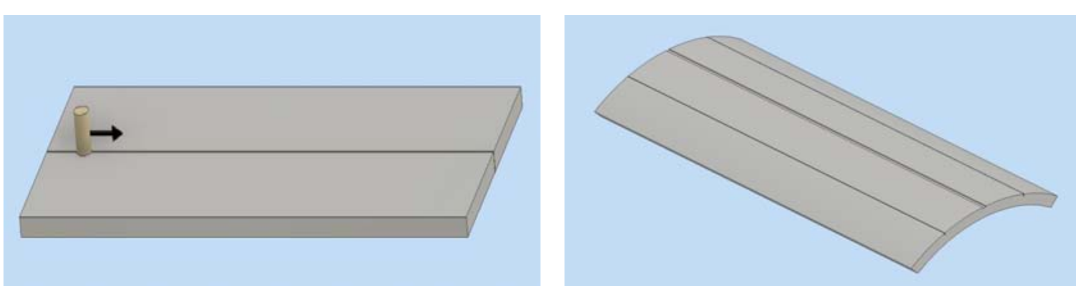
3.5.3 Design considerations

Based on the suggestions mentioned above, following considerations are put forward during the development of fixture for the experiment in this thesis:

1. The fixture developed is purely for the research experiments.
2. Base plate or backing plate should have sufficient thickness in comparison with thickness of the plates to be joined.
3. Material selected for backing plate should have low thermal conductivity which will help in maintaining the temperature sufficiently high, which will help to plasticize and displace the material.
4. Clamping from the top is required so that plates will not be lifted up from the position.
5. Horizontal movement in X and Y directions are required to be arrested.
6. Some provision is to be made to keep plates intact, so that gap in the butt region will be maintained zero or uniform minimum. Otherwise joint will not have uniform welding.

3.5.4 Different Designing Approaches

3.5.4.1 Design of fixture with single clamping from TOP



(a) (b)

Figure 3.4: (a) Plates without clamping, (b) Clamping in the vice

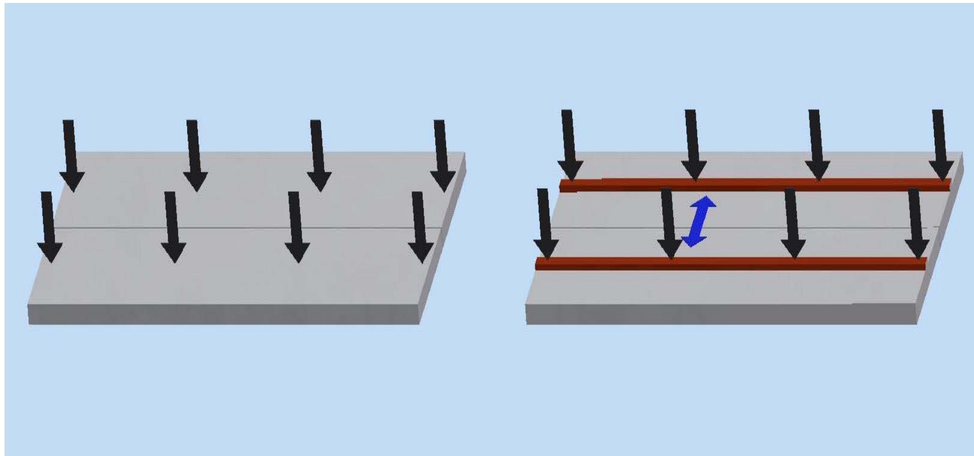


Figure 3.5: Clamping the plates from top for FSW

If clamping is not done properly or if vice is used for clamping, there are chances that the plates will get lifted up from the center at butt region (Figure 3.4). So, it was thought to apply clamping force from the top (Figure 3.5) arresting the vertical movement in Z-direction. The top clamping should be provided as close to the tool as possible, suitably 40mm to 60mm apart, which will prevent plate buckling in case of thin plates having thickness less than 6 mm. This clamping also serves the purpose of keeping the plates in contact with the backing plate at all points along the joint even if plates used are not perfectly flat.

Thus the first fixture was designed and fabricated from carbon steel for trials of FSW are shown in Figure 3.6.

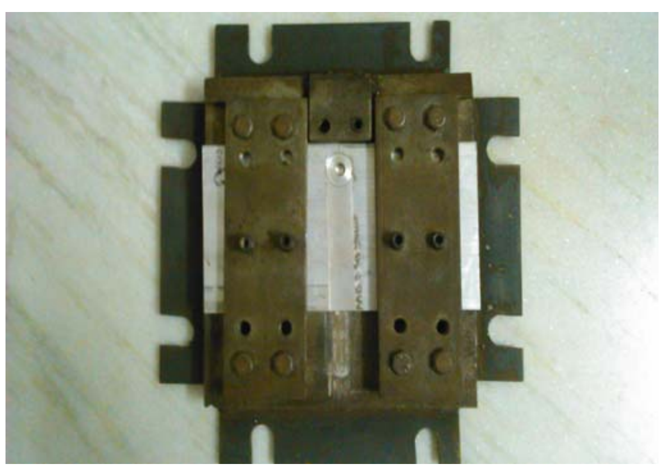


Figure 3.6: Photograph of Fixture with top clamping

As in this design, the clamping force is applied from the upper plates only. There is a possibility of splitting of the plates occur during the initial plunge and travel of tool pin along the line of the joint, Figure 3.7 [136]. A large force is required to prevent this splitting. The magnitude of this force has not been published in any literature. Care is also required to be taken to keep minimum distance between the clamping bar restraining the vertical force in the direction of plate thickness. To avoid splitting of plates, a clamping from side is required perpendicular to the line of weld.

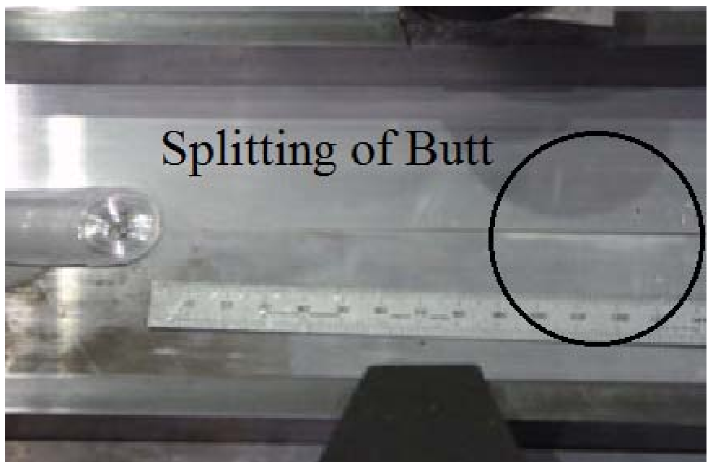


Figure 3.7: Opening of the Butt groove [136]

3.5.4.2 Design of fixture with Side Clamping

In this design we provide side clamps along with the top clamping. These side clamps can restrict the sideward movement of the plates to be welded (in X- direction) and no splitting will occur in butt region (Figure 3.8).

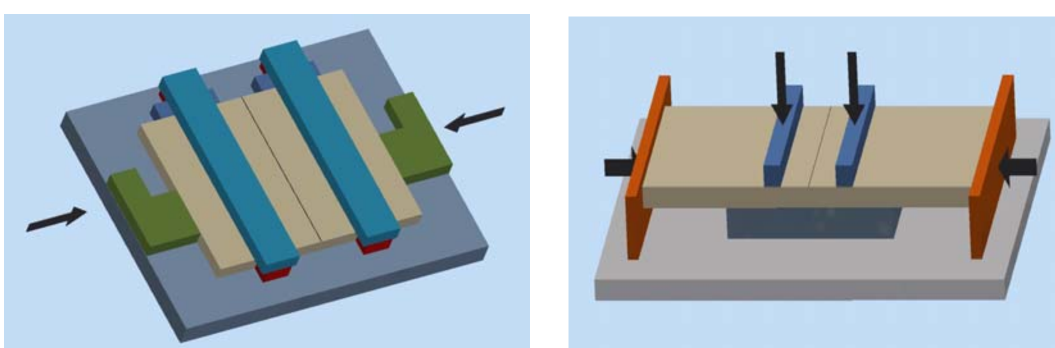


Figure 3.8: Clamping of plates from top and side with backing bar

3.5.4.3 Final design of Jig type Fixture with Variable Side Clamping

We feel that the design shown in Figure 3.8 is the correct design, but some limitations were observed in this design. And we are bound to modify this design of fixture also. Because in this design, there is a chance of sliding take place along the line of weld during tool traverse. This sliding movement is also required to be arrested.

Degrees of freedom concept adopted in design of jigs & fixture is considered partially in this jig type fixture design, for clamping the substrate to carry out research experiment. Finally plate movements were possible to be arrested which provided clamping from all the sides and which overcome the limitations of the above two designs.

Also with this design it is possible to control gap between the plates to be joined. The properties of welded joint depend on the distance between the two plates during the welding. This design of fixture will help to study the effect of substrate gap on weld properties.

The additional advantage of this fixture design is saving in setup time. No further alignment and checking required once the fixture is set on the machine table. Which will result in the net saving of production time and hence production cost.

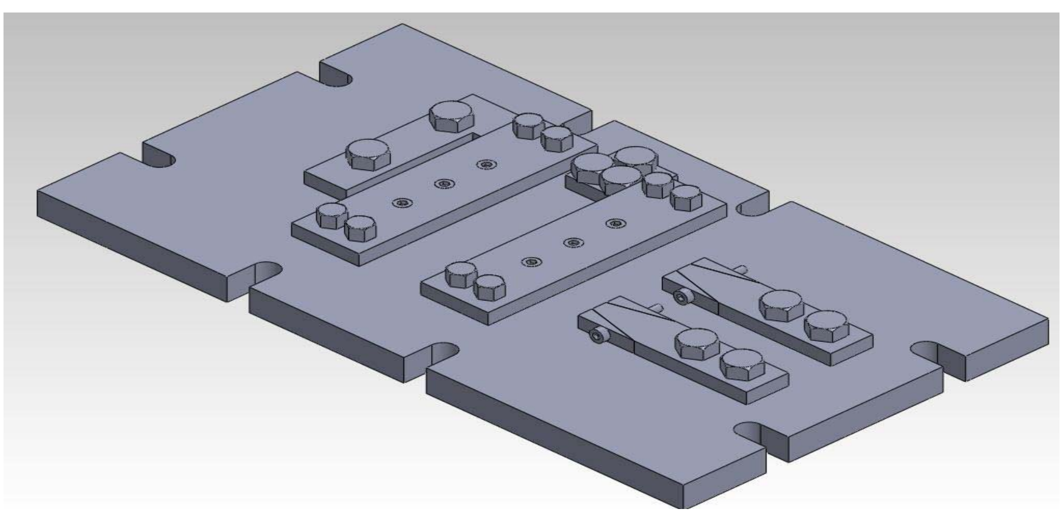


Figure 3.9: Isometric view of complete fixture assembly

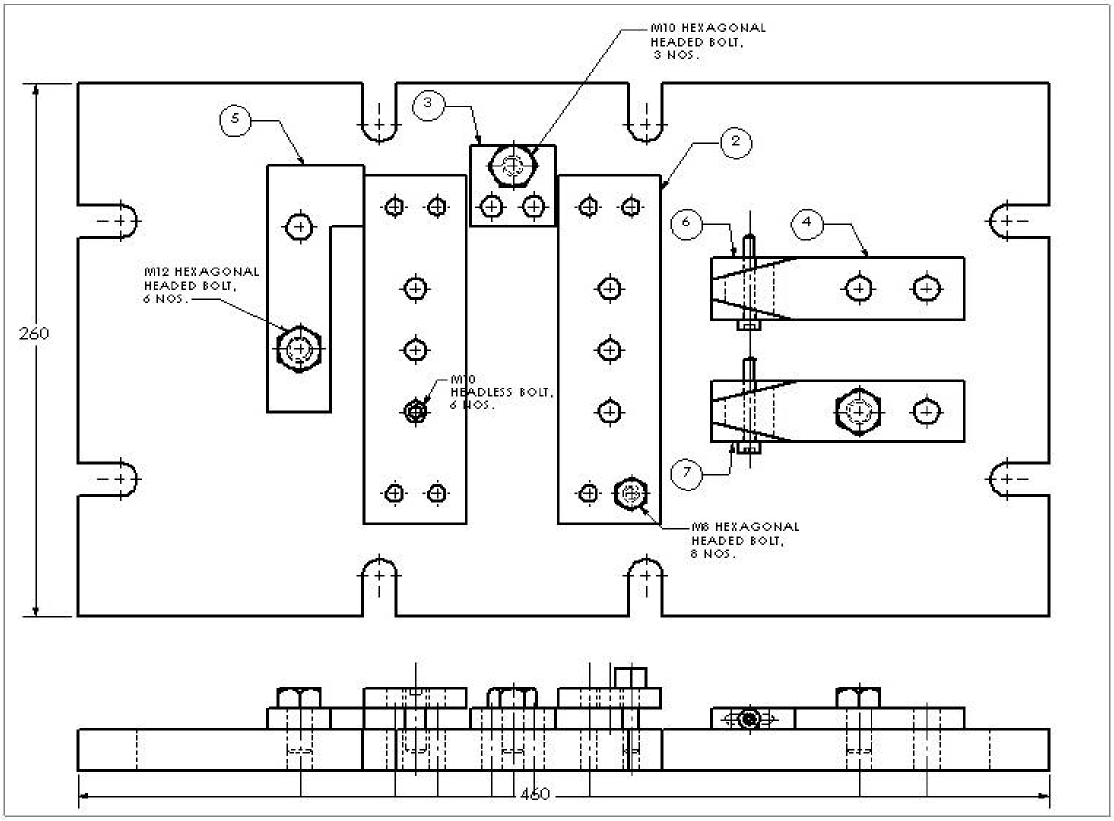


Figure 3.10: 2-D view of Jig type Fixture assembly

The first fixture (figure 3.6) was made from medium carbon steel as suggested by TWI. The second modified jig type fixture was made using backing plate from ferrite steel-430 and all other components from carbon steel.

Finally the fixture was fabricated according to its design as shown in figure 3.9 and 3.10.

3.5.5 Development of fixture for BFSW

As in case of CFSW there is no plunging phase in bobbin tool FSW. Tool is in alignment of substrates and directly welding is started from one end and finished at the other end of the plates. Initially before the actual welding is started, dwell phase was required which will plasticize the substrate material (preheating). All other factors of constraining the plate movement as in CFSW [137] are considered in the design of fixture for BFSW.

In this case function of backing plate is served by the bottom shoulder, but at the same time a provision need to be made for movement of this second shoulder. To fulfill this requirement the substrate plates should be clamped at sufficient height to accommodate and travel bottom shoulder. The other design considerations in CFSW are applicable in BFSW also. The jig type fixture designed and fabricated for BFSW (figure 3.15-3.16) is purely for research experiment for authenticity of experiment and test results. Setup time for each subsequent weld is brought to minimum is a specialty of this fixture. The different components of the fixture are as shown in figure 3.11 to 3.14.

The material selected for fabrication of fixture was carbon steel.

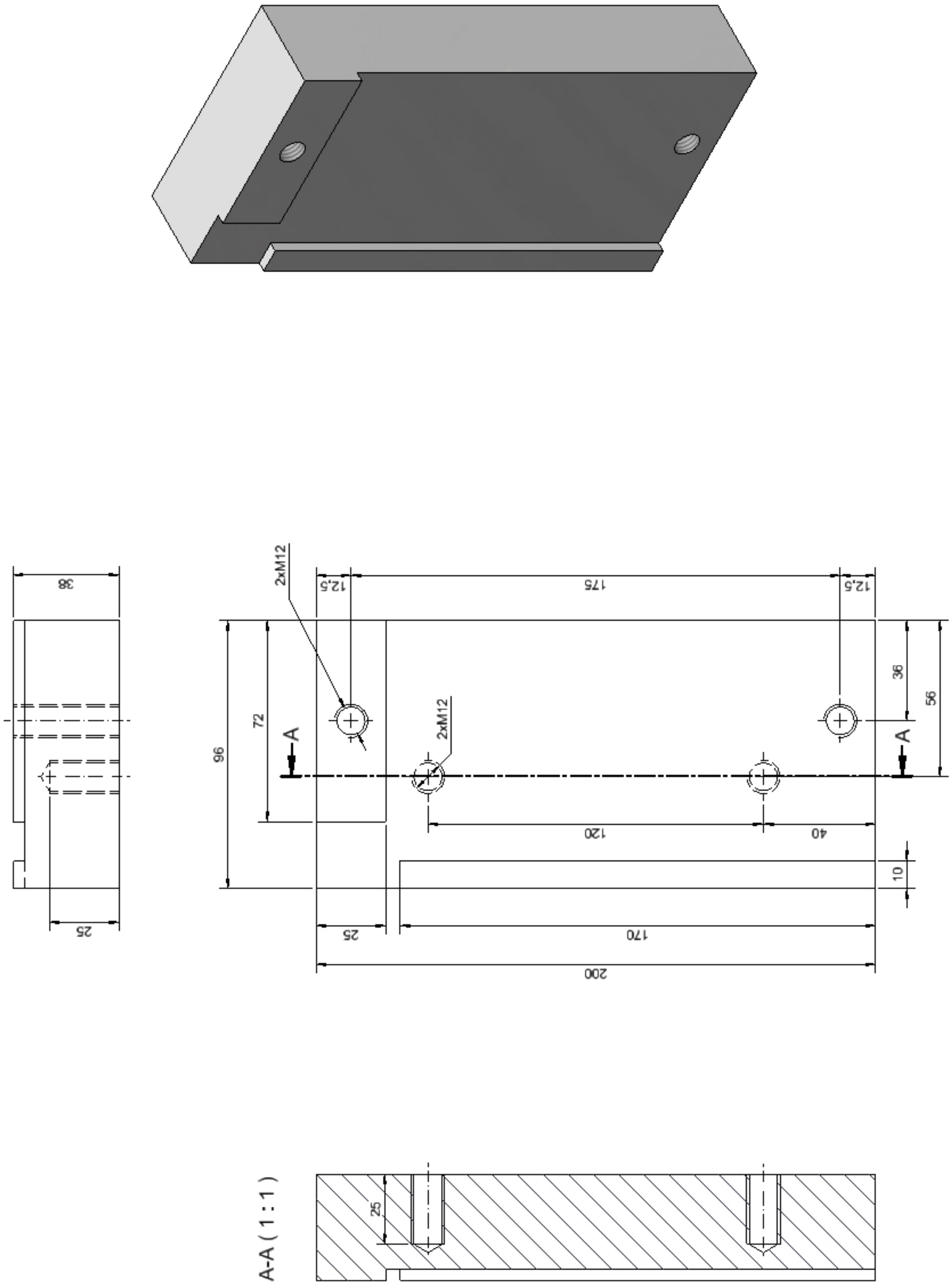


Figure 3.11: Fixture clamp support-1

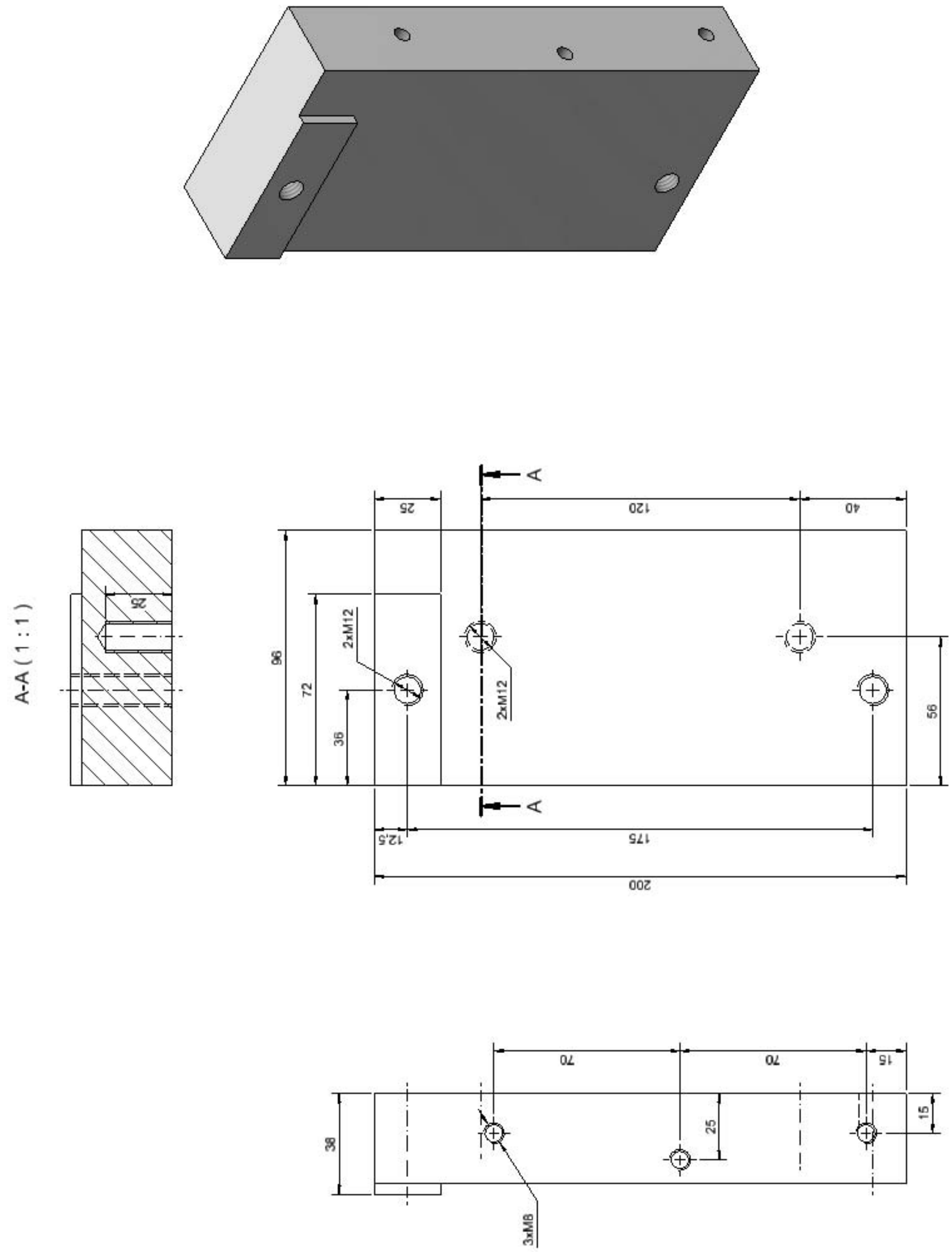


Figure 3.12: Fixture clamp support-2

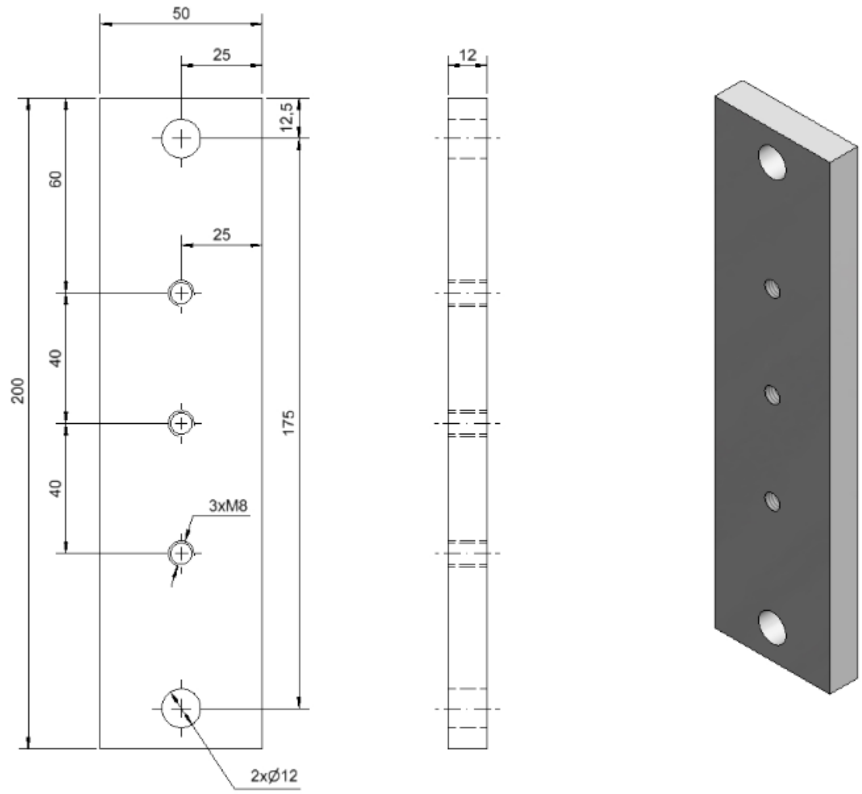


Figure 3.13: Fixture top clamping plate

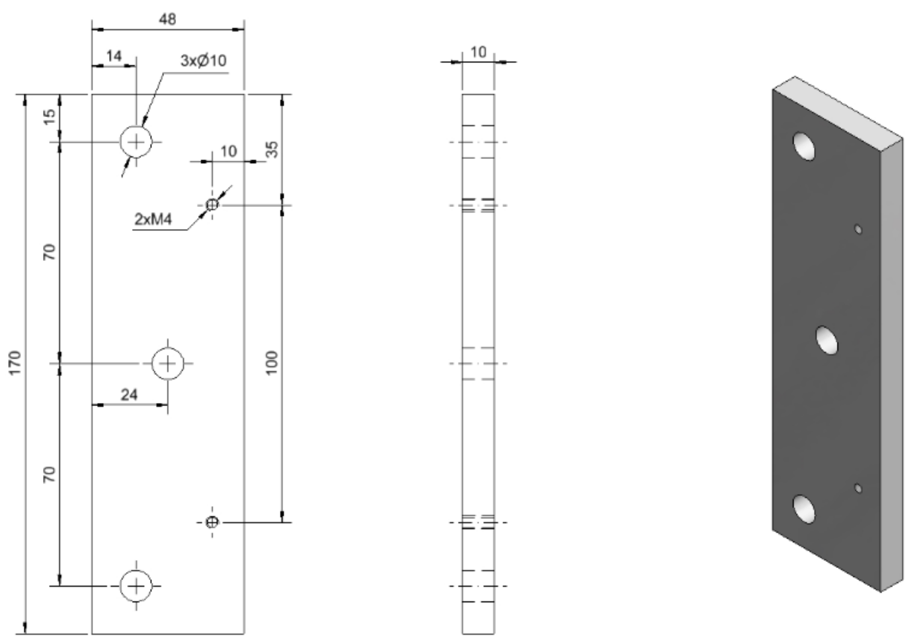


Figure 3.14: Fixture side clamping plate

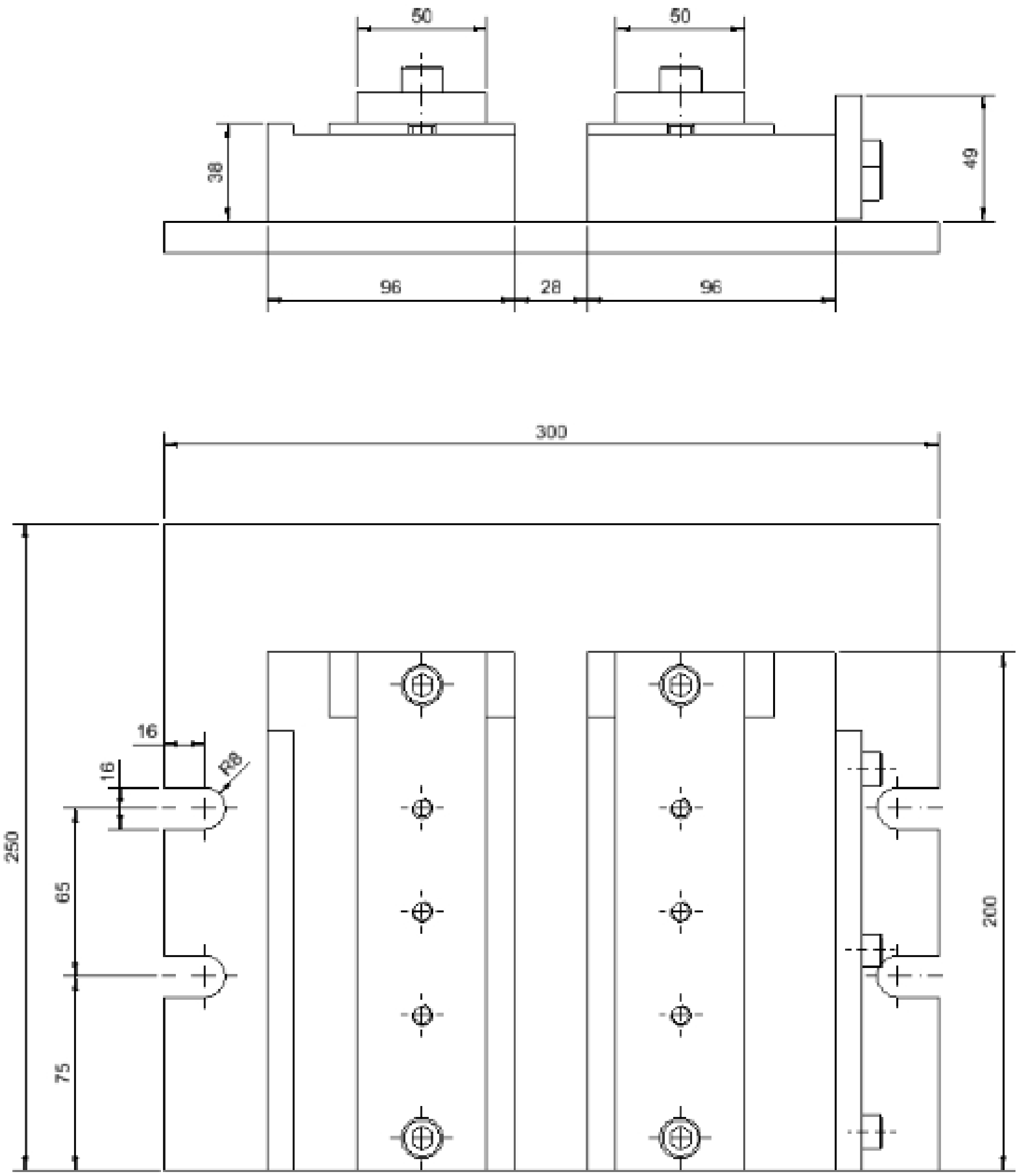


Figure 3.15: Fixture assembly for BFSW

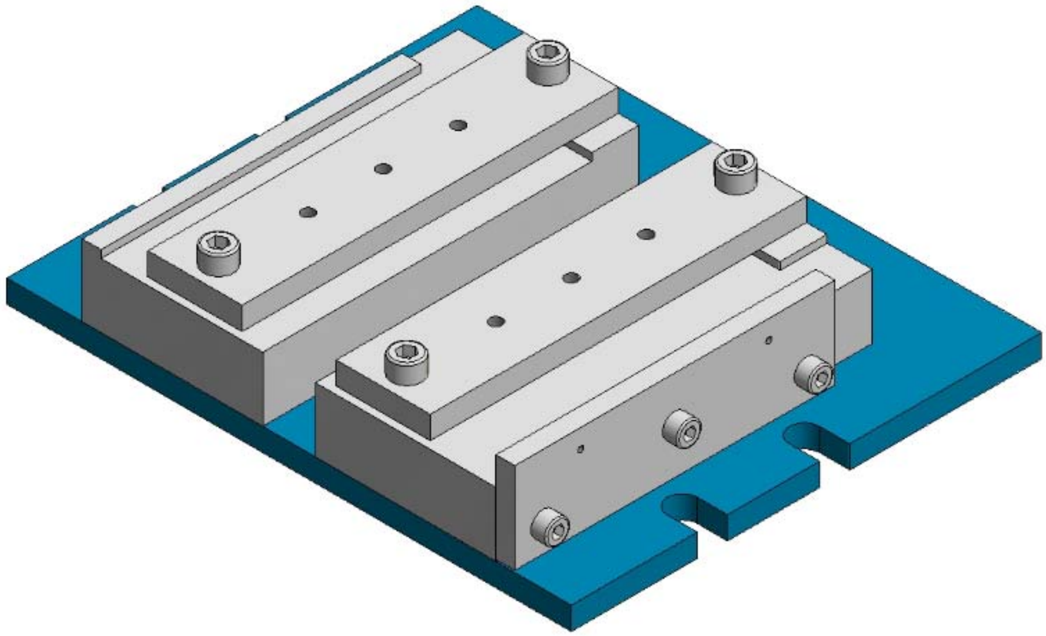


Figure 3.16: 3D view of Jig type fixture for Bobbin FSW

3.6 TOOL DESIGN

Tools play a significant role in weld formation. This is because of the direct contact between the tool surface and substrate. As a result heat is generated and material stirring takes place.

Friction stir welding uses a non-consumable rotating tool, which moves along the joint line of two plates to produce high-quality butt welds. The FSW tool is generally made with a profiled pin, which is contained in the center of a larger diameter shaft. For butt joints the length of the pin is little smaller than thickness of the work piece. The pin is traversed through the joint line while the shoulder is in contact with the top surface of the work piece.

The tool serves three primary functions:

- Heat: Heating of the work pieces
- Stir: Transfer of material to produce the joint
- Forge: Containment of the hot metal

3.6.1 Development and Fabrication of Conventional and Bobbin Tool for FSW

In this section, fabrication of conventional and bobbin tools of different features are explained. This is one of the essential hardware developments because FSW tools are known to be expensive [12]. One of the reasons is the complex tool surface features that need to be fabricated on the tool shoulder and probe. Further in case of bobbin tool it is more difficult due to limited space available between the two shoulders to achieve this. Based on background literature, tool features are important for the success of friction stir welding. This is because features such as a thread on the pin and grooves on the shoulder are important for generation of frictional heat as well as material mixing [4][138].

Some general inferences may be drawn about the effect of tool features on weld quality, based on tool design literatures as in Chapter 2.

3.6.2 CFSW tool features

i. A cylindrical threaded or conical threaded shaped pin helps in assisting material movement from top to bottom surface of the welds.
ii. The pitch between 0.8mm to 1.0 mm, or 10% of the pin diameter is considered to be more suitable in case of threaded pin profile.
iii. Direction of thread is also important with respect to the tool rotation. Left hand threads are used for CW tool rotation.
iv. Flutes and flat faced features of probe influence mixing of the weld material because of smooth plastic flow.
v. A tapered or pyramid shape pin feature should be carefully introduced.
vi. The square pin profile is able to produce a good stirring effect, but tapered square pin may not give the same results [50].
vii. The diameter of the pin should be similar to the thickness of the plate to be welded.
viii. The shoulder diameter $D = 2.3\ t + 6.9$ mm [45] L. Dubourg
ix. A concave feature on the shoulder will serve as a reservoir of material compare to the flat shoulder.

x. A convex feature on the shoulder is suitable for welding thin sheet material. For thicker material a scrolled feature needs to be applied.

xi. A fillet or chamfer on the tool is able to reduce the amount of flash.

3.6.3 BFSW tool features

i. A cylindrical pin with thread feature can produce a clear macrostructure boundary and higher bend strength. Alternatively, three flats can be used.

ii. A Tapered tool pin with three flats enables a diameter reduction in the lower shoulder which then also contributes to lower torque.

iii. For tackling high flatness variation, convex and scroll shoulder features may be suggested.

iv. Fixed and floating bobbin tool has different outputs and care must be taken to select the one. Floating tool take care of deviation in surface and torque requirement is low.

v. Assembled bobbin tool is risky. Setting up the tools was found to be inefficient. There were screws, nuts and slip gauges that involved awkward handling in order to tighten up the components as well as setting up the shoulder gap. High interference between the substrate and the tool resulted into high force and torque which ultimately can break the tool. [68].

3.6.4 CFSW tool design

It is easy to develop features on CFSW tools, but we intend to develop simple featured tools based on literature. Features that have been selected for the fabrication in this study are presented in Figure 3.17.

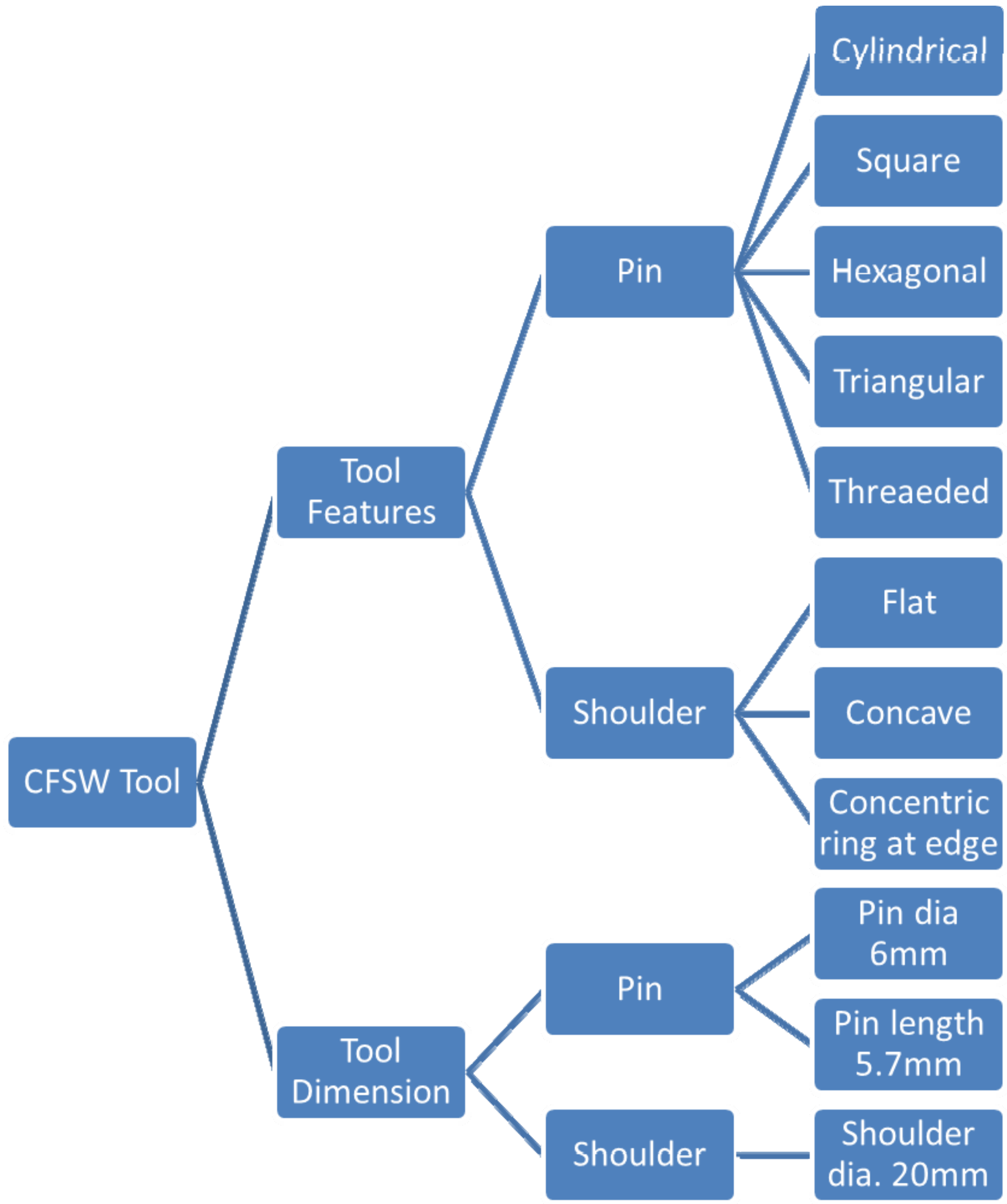


Figure 3.17: Tool features adopted for CFSW

A series of tool designs were developed and fabricated with different shoulder and pin features.

3.6.4.1 Selection of tool material

The tools are manufactured from a wear resistant material with good static and dynamic properties at elevated temperature. Tool technology has advanced considerably over the last few years and tool tips that can last up to one kilometer of weld length on 5mm thick 6xxx series aluminum alloys [139] have been developed. Since the tool creates frictional heat, high temperature gradients exist at the tool tip and shoulder. Some of the important properties that the tool material should have are good hot hardness, toughness and better high temperature strength in order to minimize tool wear.

3.6.4.1.1 The classification of Tool Steels

As a cooperative industrial effort under the sponsorship of AISI and SAE, a tool steel classification system has been developed in which the commonly used tool steels are grouped into seven major categories. These categories, several of which contain more than a single group, are listed in Table 3.5 with the symbols used for identification. Suffix numbers following the letter symbols identify the individual types of tool steels within each category.

Table 3.5: Classification of Tool Steels

Category Designation	Letter Symbol	Group Designation
High-Speed Tool Steels	M T	Molybdenum types Tungsten types
Hot-Work Tool Steels	H1-H19 H20-H39 H40-H59	Chromium types Tungsten types Molybdenum types
Cold Work Tool Steels	D A O	High carbon, high chromium types Medium alloy, air hardening types Oil hardening types
Shock Resisting Tool Steel Mold Steels	S P	… …
Special Purpose Tool Steels	L F	Low alloy types Carbon tungsten types
Water Hardening Tool Steels	W	…

3.6.4.1.2 Selection of Tool steel for Aluminum 6xxx

From to the various options of steels and alloys available it was necessary to select appropriate steel with specific characteristic behaviors that would apply to joining Aluminum 6101 and 6082 plate. During the welding process the tool will reach temperatures in the range of 400 ºC to 500 ºC at tool tip depending on the type of material being welded. The tool material must have good hardness, toughness and wear resistant properties at elevated temperatures.

A hot-work tool steel that comprises of outstanding high temperature strength, high temperature toughness, high temperature wear resistance and good machinability is W302 (H13). This tool steel selection was also motivated by its cost and availability.

Tools with specially profiled pins and optimized shoulder designs that provide large tolerance envelopes have been developed and are common in industrial applications [140]. Tool designs, optimized welding parameters and specialized clamping techniques have been developed during studies which was necessary for authentic results. Since advanced technical information on tool designs is mainly the privilege of the patent holders, we developed our own tool designs and manufacturing technology after rigorous literature study.

In the present work two different materials have been selected for tool fabrication, namely En24 steel and H13 tool steel (both hardened). Although high strength tool is essential for FSW, a cost criteria was also considered and feasibility of such tools were tested for welding different grade of materials, namely AA 6101 T6 and AA6082 T6 al alloy of 6mm thickness.

3.6.4.2 Composition of Tool material (H13 tool steel)

The EDS (Energy Dispersive Spectroscopy) analysis was done to find out the actual composition of the tool material. And the results were found to be conforming to that of the standard composition. The EDS results are given in Table 3.6.

Table 3.6: Composition of H13 tool steel

Element	Measured Weight%	Standard Weight%
C	--	0.40
Si	0.99	1.1
V	1.21	1.0
Cr	5.44	5.0
Mn	0.16	0.5
Mo	1.24	1.50

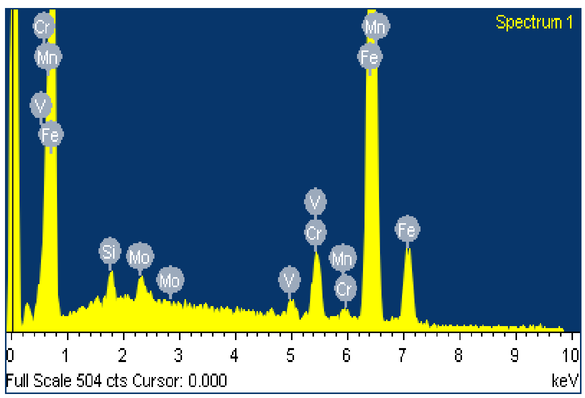


Figure 3.18: The EDS (Energy Dispersive Spectroscopy) analysis

3.6.4.3 Design of Tool Shoulder

Tool shoulders are designed to produce heat (through friction and material deformation) to the surface regions of the work piece. The tool shoulder produces a majority of the deformational and frictional heating in thin sheet, while the pin produces a majority of the heating in thick work pieces. Also, the shoulder produces the downward forging action necessary for weld consolidation (purely stick & slip phenomena). A clear trend is observed: the shoulder diameter is about 2.3 times the sample thickness plus a constant of 7 mm [45]. When the thickness increases, more energy input is necessary, this is obtained by the design of a bigger shoulder. It may also confirm that for a given sample thickness, the range of shoulder diameters may be high. In the case of a smaller shoulder, the reduction in heat generation is balanced by a higher rotational speed.

3.6.4.4 Design of Pin / probe

Friction stirring pins produce deformational and frictional heating to the joint surfaces. The pin is designed to disrupt the faying or contacting surfaces of the work piece, shear material from leading edge and move it to trailing edge of the tool. In addition the depth of the deformation and tool travel speed are governed by the pin design. Generally diameter of pin is considered to be equal to plate thickness, and pin length to be little less than the plate thickness.

Table 3.7: Different types of shoulder – pin combinations (Appendix 2)

<table>
<tr><td rowspan="2">Shoulder ⇨</td><td>Flat</td><td>Concave
Convex</td><td>Flat with half circular periphery at edge</td></tr>
<tr><td>Scroll</td><td>Concentric circles (h)</td><td>Scoop</td></tr>
<tr><td>Pin ⇩</td><td>Plain/ parallel edge</td><td>With thread</td><td>Pyramid</td></tr>
<tr><td>a</td><td colspan="3">Plain cylindrical</td></tr>
<tr><td>b</td><td colspan="3">Conical / Truncated cone</td></tr>
<tr><td>c</td><td colspan="3">Square</td></tr>
<tr><td>d</td><td colspan="3">Triangular</td></tr>
<tr><td>e</td><td colspan="3">Hexagonal</td></tr>
<tr><td>f</td><td colspan="3">Threaded cylindrical</td></tr>
<tr><td>g</td><td colspan="3">Truncated cone with thread</td></tr>
<tr><td>h</td><td colspan="3">Pin bottom – flat, round</td></tr>
</table>

3.6.4.5 Different tools used in this experiment are shown in Figure below.

1) CFSW tool used for AA 6101 T6 alloy was made from En24 steel with hexagonal pin and concave shoulder (Figure 3.19).

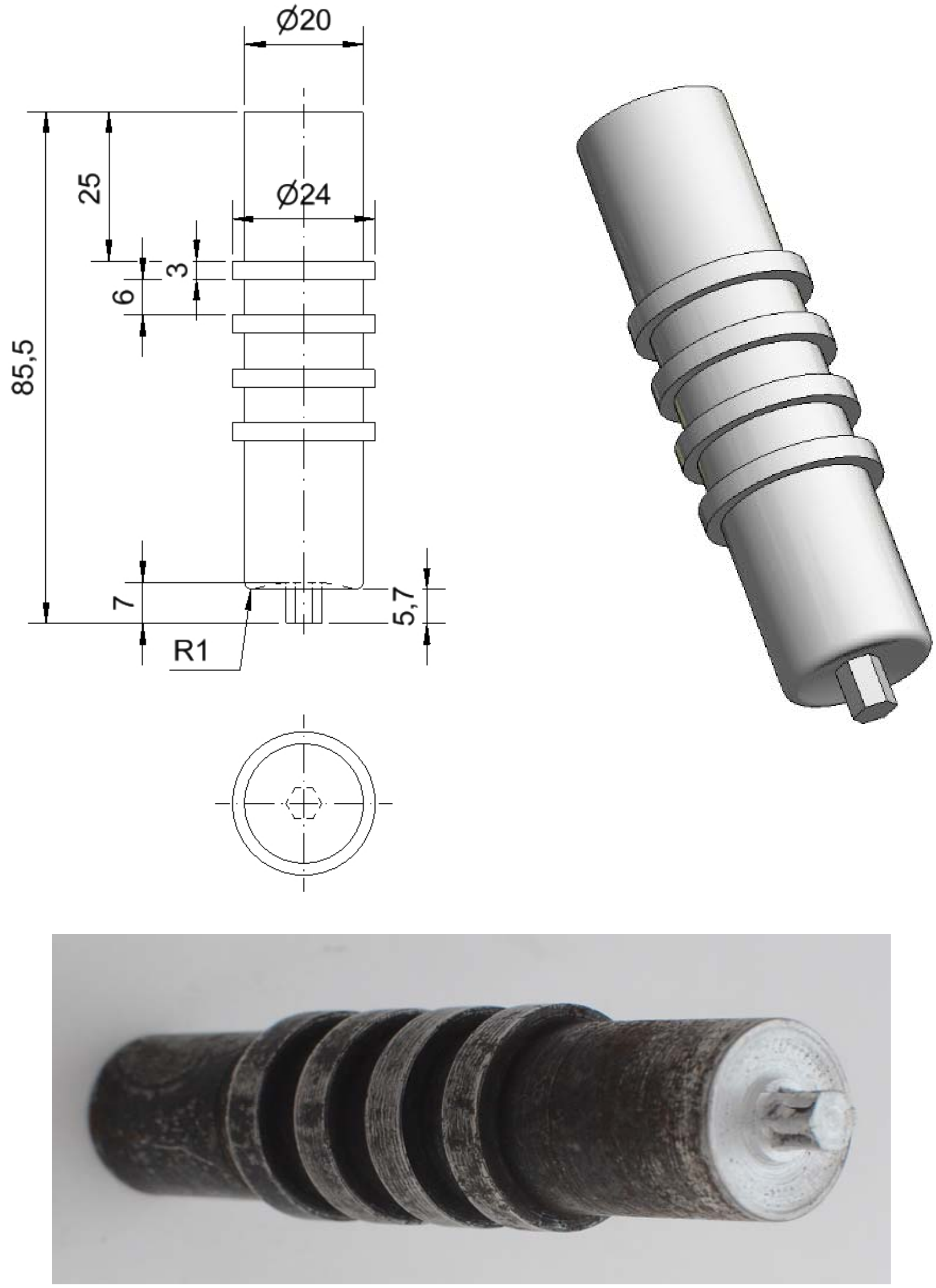


Figure 3.19: Tool geometry used for the friction stir welding of AA 6101 T6 alloy Hexagonal pin profile with concave shoulder (C1)

2) Tool used for AA 6101 T6 alloy was made from H13 tool steel with square pin and flat shoulder feature. Figure 3.20.

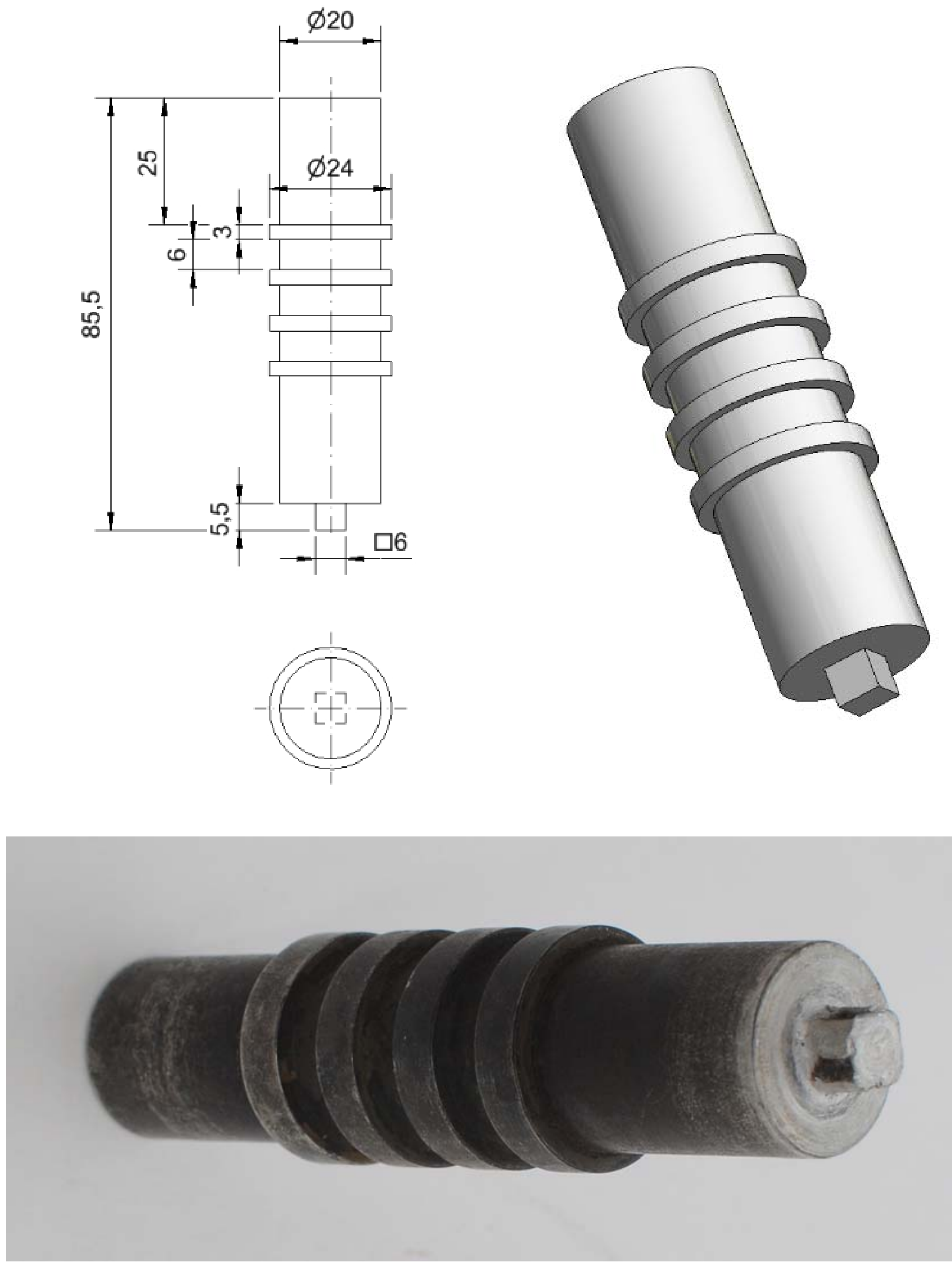


Figure 3.20: Tool geometry used for the friction stir welding of AA 6101 T6 alloy - Square pin profile with flat shoulder (C2)

3) Tool used for AA 6101 T6 alloy was made from H13 tool steel with square pin, and shoulder with semicircular ring at the edge Figure 3.21.

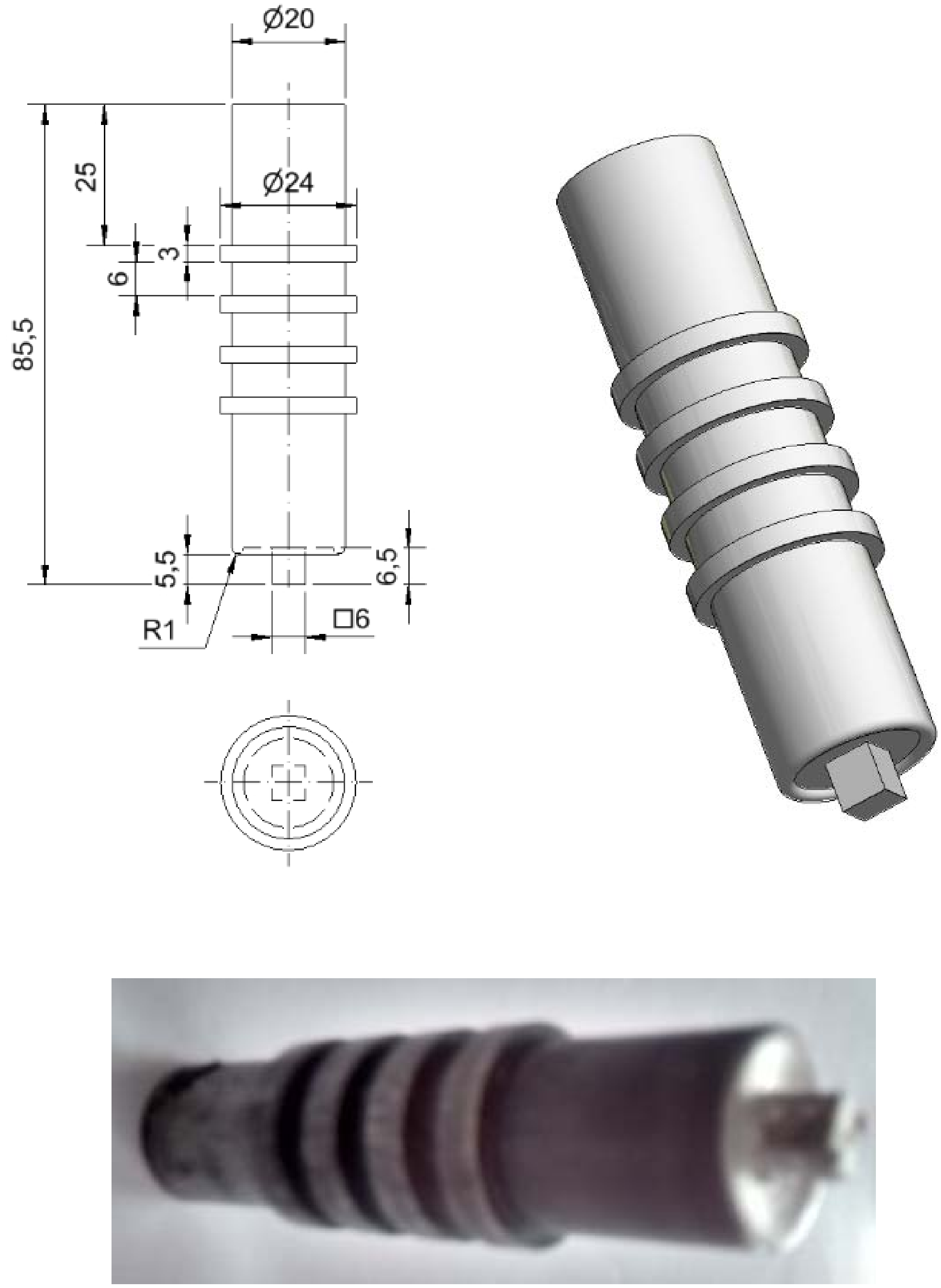


Figure 3.21: Tool square pin and shoulder with semicircular ring at the edge (C3)

4) For welding AA 6082 T6 alloy tool was made from H13 tool steel with square pin and concave shoulder feature. Figure 3.22.

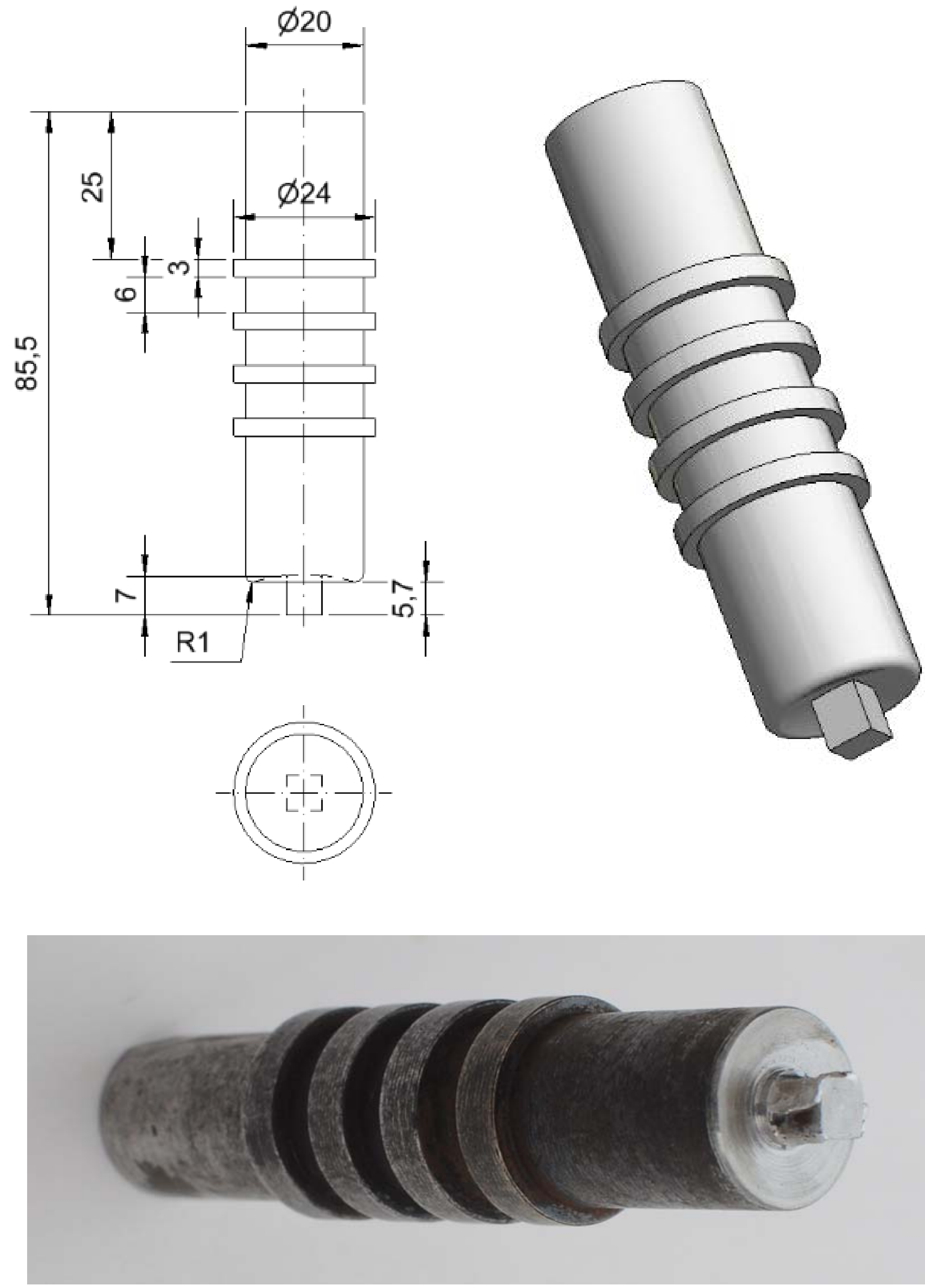


Figure 3.22: Tool geometry used for the friction stir welding of AA 6082 T6 alloy square pin and concave shoulder (C4)

3.6.4.6 BFSW Tool

To produce the features for a single sided tool as in CFSW it is not difficult as there is sufficient working space for the cutting tool to access the area. This is not the case for bobbin tools for the BFSW process. The reason is because of limited gap available between the shoulders. While simple bobbin tools may be machined out of a single piece of material, the machining is difficult when dealing with complex features which require specialist tools.

Similar to CFSW, features that have been selected for the fabrication in this study are presented in Figure 3.23.

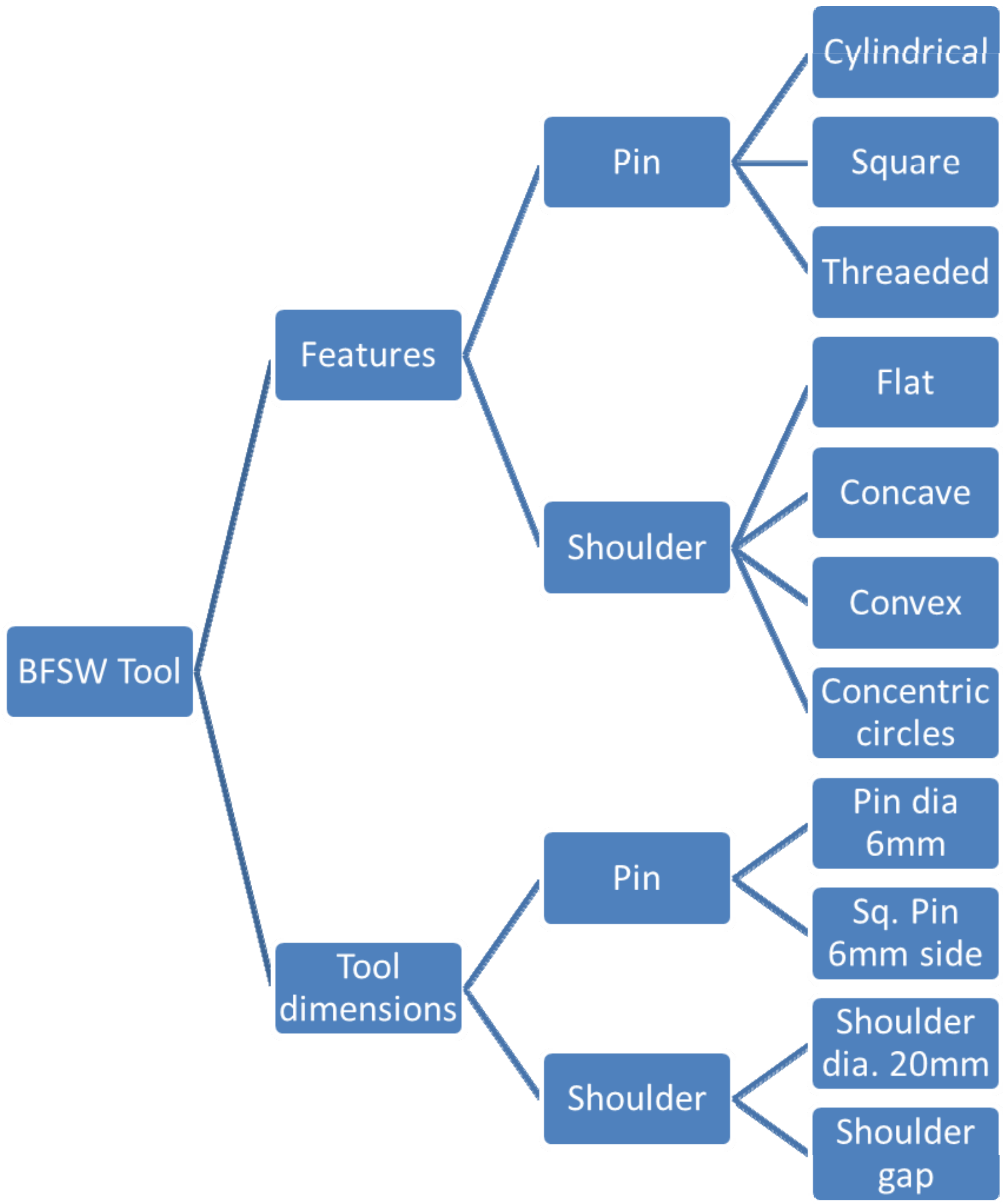
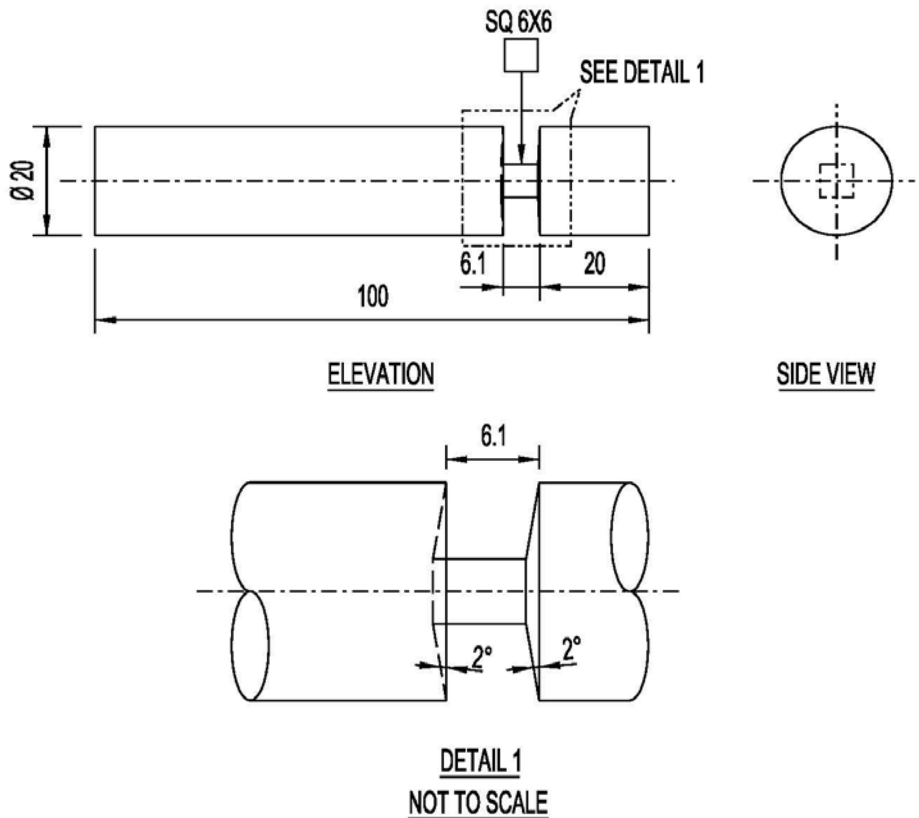


Figure 3.23: Tool features adopted for BFSW

1) For welding AA 6082 T6 alloy, a fixed gap bobbin tool with square pin, concave-convex shoulder was made from H13 tool steel shown in the figure 3.24.



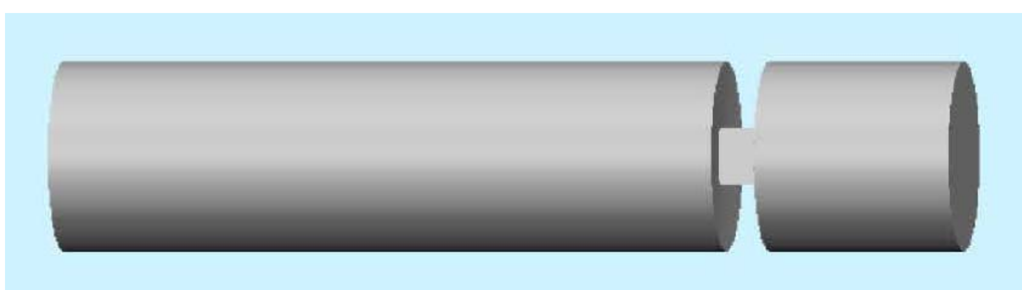


Figure 3.24: Fixed gap bobbin tool with square pin, concave-convex shoulder BT1

2) For welding AA 6082 T6 alloy, a fixed gap bobbin tool with square pin, convex-convex shoulder was made from H13 tool steel shown in the figure 3.25.

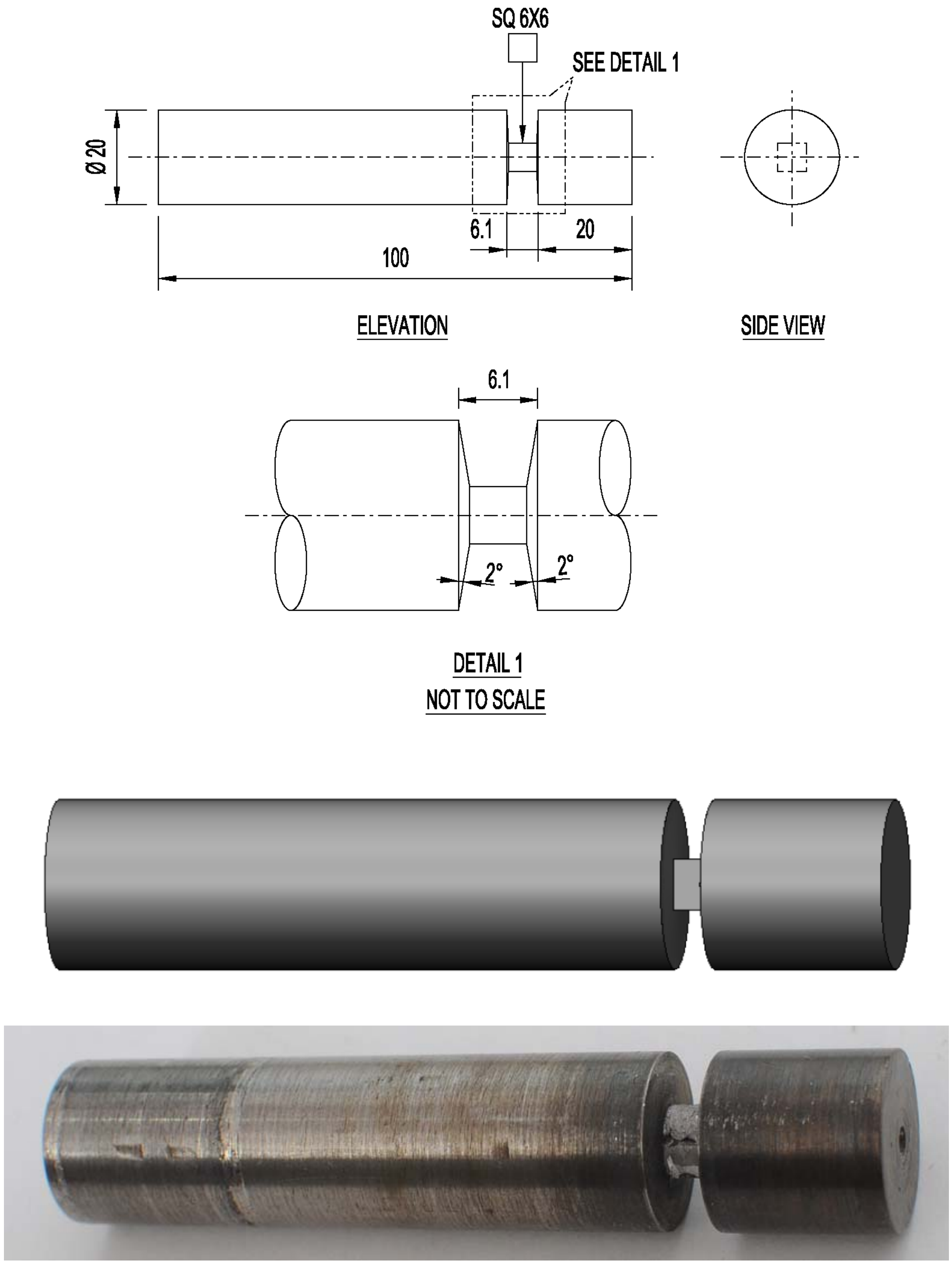


Figure 3.25: Fixed gap bobbin tool having square pin, convex - convex shoulder BT2

3.6.5 In-house experimental set up developed for conventional friction stir welding

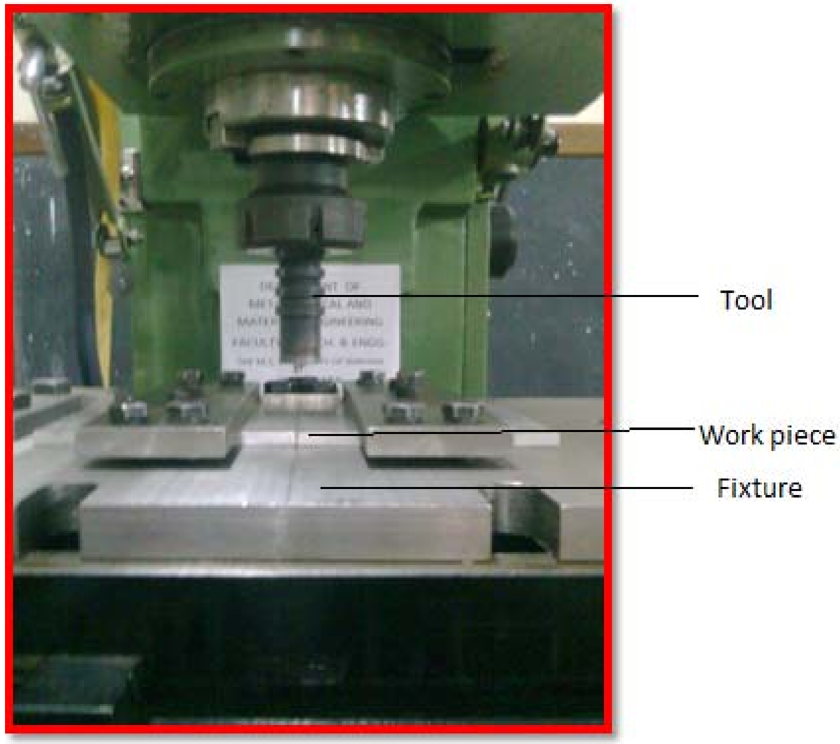


Figure 3.26: Experimental set up developed in-house for experiment

3.6.5.1 Set-up for BFSW on CNC milling machine.

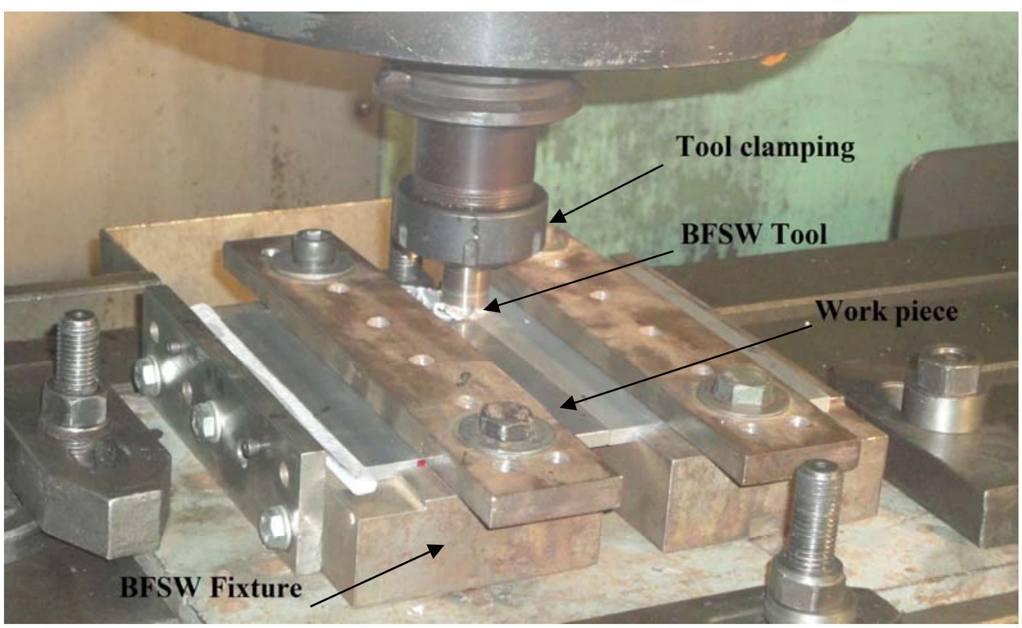


Figure 3.27: Bobbin Friction Stir Welding setup

3.7 SELECTION OF PROCESS PARAMETERS

3.7.1 Parameters selected for CFSW of AA 6101 T6 Al alloy (Table 3.8)

Tool specifications: **C1**

- Shoulder : Concave
- Pin : Hexagonal
- Tool material : En 24 steel
- Shoulder diameter: 20 mm
- Pin length : 5.7 mm

Welding platform used: Vertical milling machine (conventional)

(As given in C2 tool)

Table 3.8: Welding parameters for CFSW of AA6101 T6 with hexagonal pin tool

Experiment No	Tool rotation speed RPM	Welding speed mm/min
E1 A	545	50
E1 B	545	50
E2	545	78
E3	545	120
E4	765	50
E5	765	78
E6	765	120
E7	1070	50
E8	1070	78
E9	1070	120

3.7.2 Parameters selected for CFSW of AA 6101 T6 Al alloy (Table 3.9)

Tool specifications: **C2**

- Shoulder : Flat
- Pin : Square 6mm side
- Tool material : H13 tool steel
- Shoulder diameter: 20 mm
- Pin length : 5.7 mm

Welding platform used: Vertical milling machine (conventional).

Technical specifications

- SIGMA- Model VM2 – light duty vertical milling machine
- Table size : overall 1340x250 mm, clamping area 975x250
- Table movement : longitudinal 700mm, cross 250mm, vertical 400mm
- Spindle nose taper : ISO 40
- Spindle speed variable: Range 35 to 1500 rpm
- Feed range : 20 to 800mm/min
- Spindle motor : 3.7/5 kw/hp., feed motor 1.1 kw/1.5 hp.
- Machine size : height 1900 mm, width 1575 mm, height 2360 mm.
- Machine weight with standard accessories: 2000 Kg
- Operating voltage : 415 V, 3Ph, 50 Hz

Table 3.9: Welding parameters for CFSW of AA6101 T6 using square pin tool

Experiment code	E10	E11	E12
Tool rotation speed RPM	545	765	1070
Welding speed mm/min	78	78	78

3.7.3 Parameters selected for CFSW of AA 6101 T6 Al alloy (Table 3.10)

Tool specifications: **C3**

- Shoulder : Flat with semicircular ring at the edge
- Pin : Square 6mm side
- Tool material : H13 tool steel
- Shoulder diameter: 20 mm
- Pin length : 5.7 mm

Haas CNC Milling machine Specifications

- Table Size : 36" X 12"
- Travels : X Axis 16", Y Axis 12", Z Axis 10"
- Table Load Capacity : 500 lbs.
- Spindle Drive Motor : 15 hp.
- Spindle Speeds : 10,000 Rpm
- Drive System : Direct Speed Belt Drive
- Spindle Taper : BT 40
- Tools : 10
- Rapid Traverse Rates : (X, Y, Z) 1200 in/min.
- Control : Fanuc CNC Control
- Electrical Supply : 220 Volt/ 3 Phase /60 Hertz
- Weight : 3400 lbs.

Table 3.10: Parameters for CFSW of AA 6101 T6 Al alloy

Expt. Code no.	Rotational speed RPM	Welding speed m/min.
A01	800	20
A02	800	60
A03	800	40
A04	1000	20
A05	1000	60
A06	1000	40
A07	1200	20
A08	1200	60
A09	1200	40

3.7.4 Parameters selected for CFSW of AA 6082 T6 Al alloy (Table 3.11)

Tool specifications: **C4**

- Shoulder : Concave
- Pin : Square 6mm side
- Tool material : H13 tool steel
- Shoulder diameter: 20 mm
- Pin length : 5.7 mm

Welding platform used: Vertical milling machine (conventional).
Machine specifications: (as given in C2 tool)

Table 3.11: Parameters for CFSW of AA 6082 T6 Al alloy

Code no.	CS1	CS2	CS3	CS4	CS5	CS6	CS7
Rotational speed RPM	1070	1070	1070	1070	1070	1070	1070
Welding speed mm/min.	48	78	125	155	200	315	500

3.7.5 Parameters selected for BFSW of AA 6082 T6 Al alloy (Table 3.12)

Tool specifications : **BT1**

- Top Shoulder : Concave
- Bottom Shoulder : Convex
- Pin : Square 6mm side
- Tool material : H13 tool steel
- Shoulder diameter : 20 mm

Welding platform used : CNC milling machine.

MORI SEIKI Vertical Machining Center

Model NV5000AI

- Table Size : 43.30" X 23.60"
- Travels : X Axis 40.2", Y Axis 20.10", Z Axis 20.10"
- Table Load Capacity : 2,200 lbs.
- Spindle Drive Motor : 30 hp.

- Spindle Speeds : 14,000 Rpm
- Spindle Taper : Cat 40
- Tools : ATC 30
- Rapid Traverse Rates : (X, Y, Z) 1650 ipm.
- Control : Siemens CNC Control
- Electrical Supply : 220 Volt/ 3 Phase /60 Hertz
- Max Dimensions : 150" X 106" X 110"
- Weight : 15,000 lbs.

Table 3.12: Parameters for BFSW of AA 6082 T6 Al alloy with square pin concave-convex shoulder tool

Code no.	BS1	BS2	BS3
Rotational speed RPM	800	600	600
Welding speed mm/min.	48	48	24

3.7.6 Parameters selected for BFSW of AA 6082 T6 Al alloy (Table 3.13)

Tool specifications: **BT2**

- Shoulder : Convex
- Pin : Square 6mm side
- Tool material : H13 tool steel
- Shoulder diameter: 20 mm

Welding platform used: CNC machine.

Technical specifications

As given in BT1 tool

Table 3.13: Parameters for BFSW of AA 6082 T6 Al alloy with square pin convex shoulder tool

Code no.	B1	B2
Rotational speed RPM	1000	800
Welding speed mm/min.	24	24

3.8 MECHANICAL TESTS FOR FRICTION STIR WELDED SAMPLES OF AL ALLOY

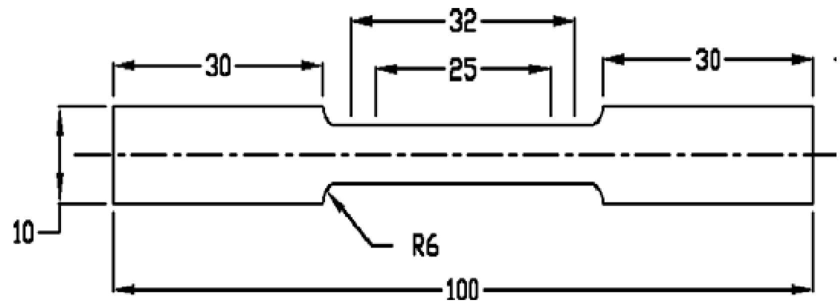
3.8.1 Tensile Test as per ASTM E8 Standard

The tensile testing of the weld sample was carried out as per the ASTM E8 standard, the dimension of the test specimen is indicated in the following table 3.14 (Figure 3.28).

Table 3.14: Dimension of Tensile specimen as per ASTM E8 standard

Dimension for Sub size specimen for Tensile test	
Gage length	25 mm
width	6.25mm
Radius of Fillet	6 mm
Overall length	100 mm
Length of reduced section	32 mm
Length of grip section	30 mm
Width of grip section	10 mm

(a)



(b)

Figure 3.28: Tensile test (a) U.T.S. Machine (b) Dimension of the tensile test specimen

3.8.2 Face Bend Test

The face bend test of the weld sample was carried out in a vision to check the side wall fusion of weld sample and also the ductility of the weld. The face bend test of weldments was carried out as per ASME section IX (see table 3.14). The experimental set up for bend test is indicated in the following Figure 3.29.

Table 3.15: Test parameters for Face bend test

Test parameter	
Bending diameter of mandrel	4(T) = 24mm
Bending angle	180º

(a)

(b)

Figure 3.29: Experimental set up for the Bend test (a) Before Bend test (b) After Bend test

3.8.3 Brinell Hardness Test

The Brinell hardness test was carried out using the 2.5 mm diameter of hardened steel ball indenter & 31.25 kg load. The hardness profile was carried out across the welding direction from base metal at advancing side to base metal at retreating side of samples. The following figure 3.30 shows the hardness tester utilized for the Brinell Hardness testing.

Figure 3.30: Hardness tester

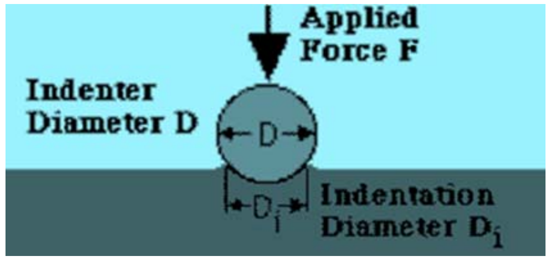


Figure 3.31: Figure showing the schematic view of indenter & indentation.

The following equation was used to calculate the BHN value (figure 3.31).

$$\mathrm{BHN} = \frac{2P}{\pi D\left(D - \sqrt{(D^2 - d^2)}\right)}$$

Where,

P = Applied load, kg

D = Diameter of indenter, mm

d = Diameter of indentation, mm

3.9 CONDUCTIVITY MEASUREMENT

AA 6101 T6 is the alloy that possesses the highest electrical and thermal conductivity among all other 6xxx Al alloy. The AA 6101 T6 is widely used for making electrical Bus bar conductor. Generally bus bar used in substations or high-rise buildings is either lap joint or single or double strap butt joint bolted with bolt, washer and nut. To carry current in this case requires proper joint and tightening of bolts. After friction stir welding one should see that the joint possess the electrical conductivity near to the base metal. The electrical conductivity measurement was carried out using the digital conductivity meter with reference to International Annealed Copper standard. The following figure 3.32 indicates a digital electrical conductivity meter utilized for measurement.

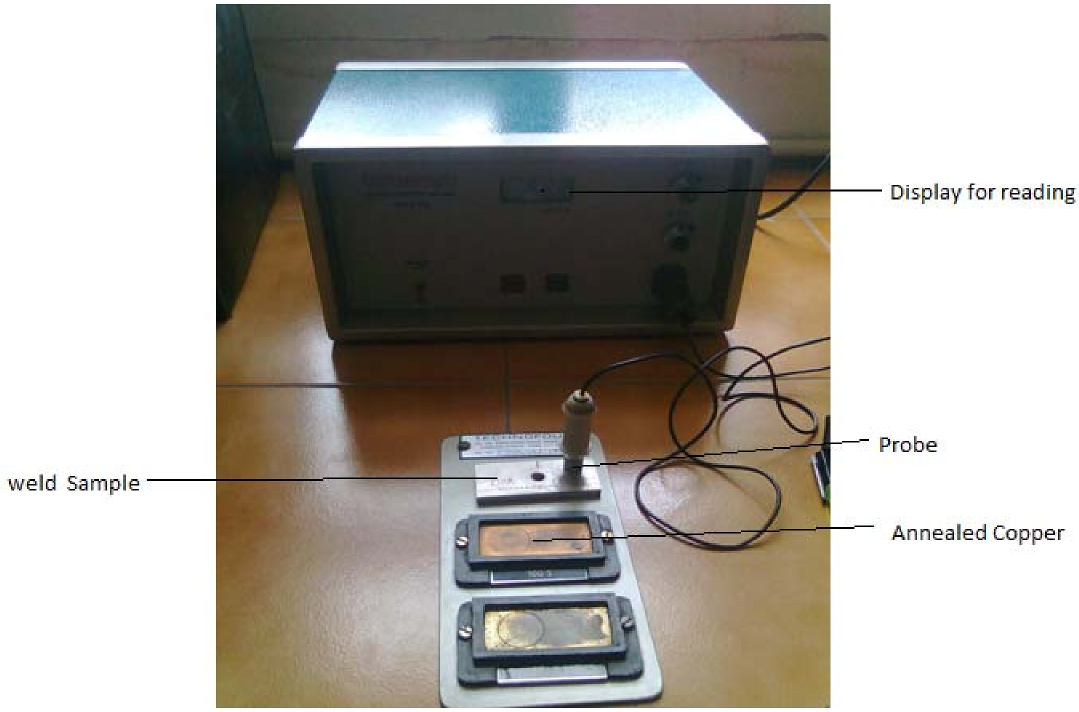


Figure 3.32: Digital Electrical Conductivity meter.

3.10 CHARACTERIZATION STUDY

3.10.1 Metallography of friction stir welded AA 6101 T6 and AA 6082 T6 alloy sample

For the microstructure analysis, the samples were cut into the required size. The section was taken across the welding direction. Then the samples were polished on the belt grinder (figure 3.33) to get scratches in the one direction. The intermediate polishing was carried out on 1/0(400), 2/0(300), 3/0(200) & 4/0(100) SiC emery paper. As the aluminum & its alloys are considered to be light metals, the emery paper was lubricated with kerosene. The sample was rubbed on the emery paper till all the scratches are in the same direction. The direction was changed perpendicular to the previous scratches with change in the emery paper. The fine polishing (figure 3.34) was carried out on the velveteen cloth with the alumina powder as abrasive and kerosene as liquid media. The use of water is avoided to decrease or to eliminate the risk of Mg_2 Si particle loss. The final polishing is carried out using diamond paste (Figure 3.34 (b)).

Figure 3.33: Belt Grinding machine for initial grinding of samples

(a)

(b)

Figure 3.34: Polishing machines (a) Alumina polishing (b) Diamond paste polishing

.

3.10.2 Etchant used for AA 6101 T6 alloy and AA 6082 T6 alloy

- Etchant : 4M Keller (in dilute form)
- Hydrofluoric acid : 6 ml
- Hydrochloric acid : 12ml
- Nitric acid : 22 ml
- Distilled water : 60 ml
- Immersion time : 1 to 3 min

The microstructure analysis was carried out on metallurgical microscope at 100x, at Neophot at 250x, and at SEM (Figure 3.35) at 250x magnification.

Figure 3.35: Scanning Electron Microscope (model: JEOL JSM 5610 LV)

3.11 CYCLIC POLARIZATION TEST TO STUDY CORROSION RESISTANCE

3.11.1: Cyclic Polarization Test (ASTM G61-86, 2009)

The electrochemical technique that has gained the most widespread acceptance as a general tool for assessing the possibility of an alloy suffering localized corrosion is probably the cyclic potentiodynamic polarization technique. This test is carried out under the ASTM G61-86 (2009) practice. The cyclic potentiodynamic polarization technique for corrosion studies was introduced in the 1960s and refined during the 1970s into a fairly simple technique for routine use. In this technique, the voltage applied to an electrode under study is ramped at a continuous rate relative to a reference electrode using a potentiostat.

The voltage is first increased in the anodic or noble direction (forward scan). At some chosen current or voltage, the voltage scan direction is reversed toward the cathodic or active direction (backward or reverse scan). The scan is terminated at another chosen voltage, usually the corrosion potential or some active potential. The corrosion behavior is predicted from the structure of the polarization scan. Though the generation of the polarization scan is simple, its interpretation can be difficult.

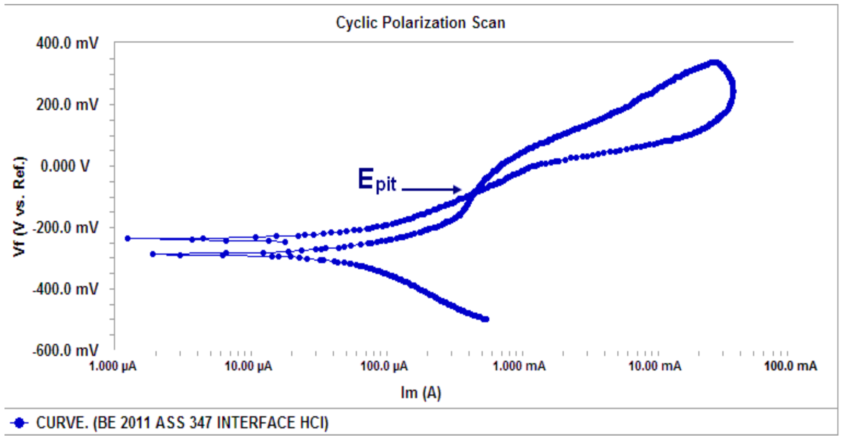


Figure 3.36: Negative hysteresis

Reverse scan current density less than forward scan current density.

Epit>Ecorr.

Pitting will occur but damage passive film will repaired & protecting it from further corrosion.

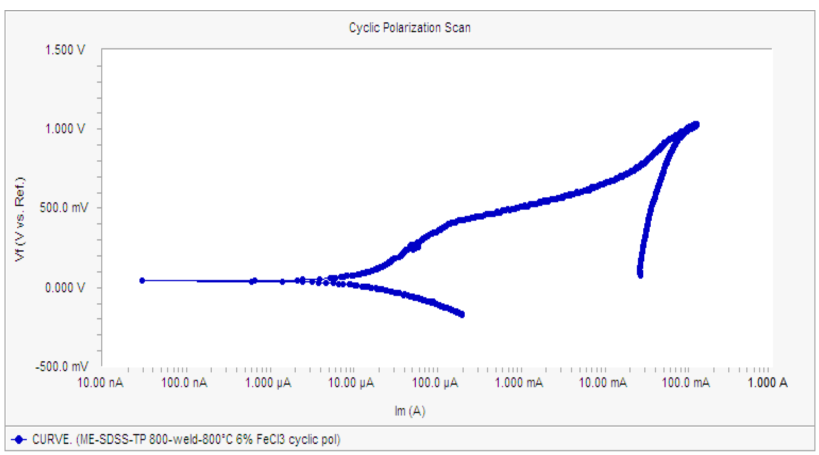


Figure 3.37: Positive hysteresis

Reverse scan current density greater than forward scan current density.

Epit<Ecorr.

Pitting will occur and corrosion rate will increase because damage passive film will not repaired.

3.11.2 Potentiostat

- **Model**: EG&G PAR 273A & Gamry Potentiostat (Reference 600).
- **Software**: M273 & M398.
- **Attachments**: Computer system for data storage.
- **Cell: -** 3 Electrodes
    - Working electrode (Sample Specimen)
    - Reference electrode (standard Calomel electrode)
    - Auxiliary electrode (Graphite)
- **Principle: -** Works on the principle of Wheatstone bridge.

3.11.3 Preparation of sample & solution for corrosion studies

The samples should be in the form of narrow strips which is to be tested.
The surface of the samples to be exposed is polished by conventional grinding and polishing methods.
The masking of the metals strips by masking tapes was done to expose a selective surface for maintaining the area ratio.
Take a container and rinse it with distilled water. Weigh 35 grams of NaCl and add it to the container. Add distilled water to the container to make the bath volume to 1 liter. 3.5 % NaCl is most naturally occurring highly corroding environment.
The sample is covered with adhesive masking tape of water resistant quality. Then an exposed area of 0.25 cm^2 is cut at one end and electrical connections are provided at other end the sample is exposed to the corrosive environment. Before this a continuity check is done where the continuity of the exposed area of the sample with the other end of the supply is checked by a digital multimeter.

The cell is consisting of one counter electrode made up of graphite which is considered as inert. The cell also contains a standard electrode which is a Saturated Calomel electrode (SCE).

The following flow diagram (figure 3.38) explains the working of software and working of Potentiostat.

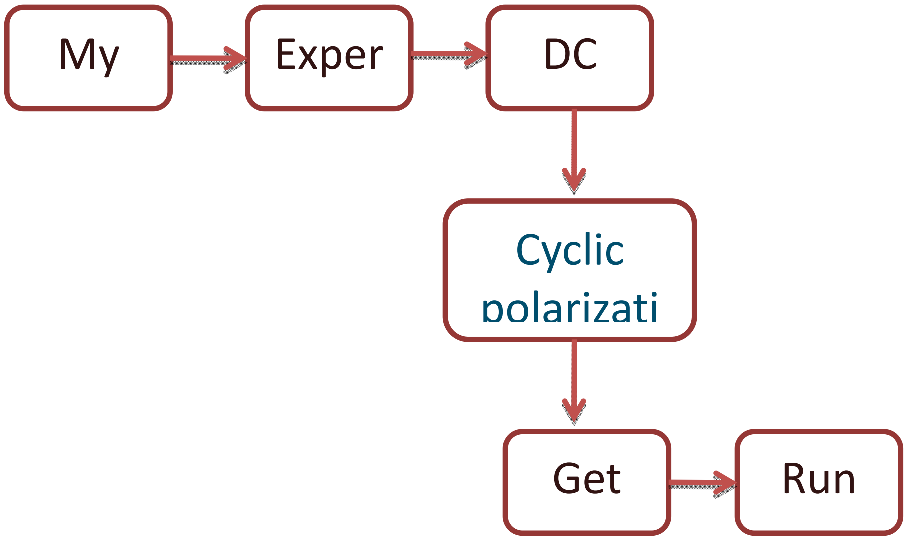


Figure 3.38: Flow sheet of cyclic polarization test procedure.

The software has many other facilities by which it converts the graph into various other forms as required and automatically calculates the values of E_{corr}, I_{corr}, Tafel slope, corrosion rate, etc. The software can also overlay various curves and helps to get the comparative study of various different samples. The Software can also store the data setup for future use and further editing work. The curves obtained can be easily transferred to Windows and also can be printed in both graph and tabular form. The software also contains a help command which gives proper guidance for getting complete advantage of all the facilities which the software provides.

Figure 3.39: Test set up used in cyclic polarization test

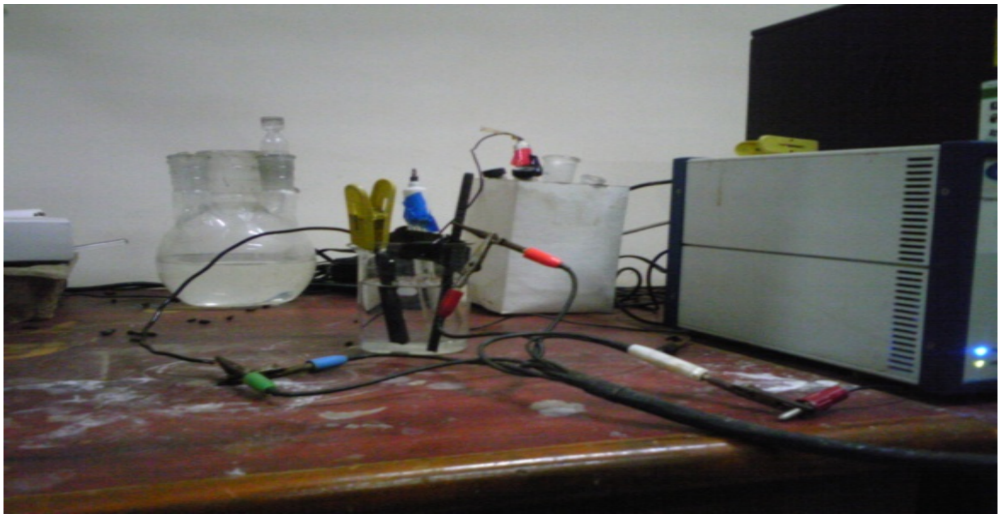


Figure 3.40: Cell used in cyclic polarization test

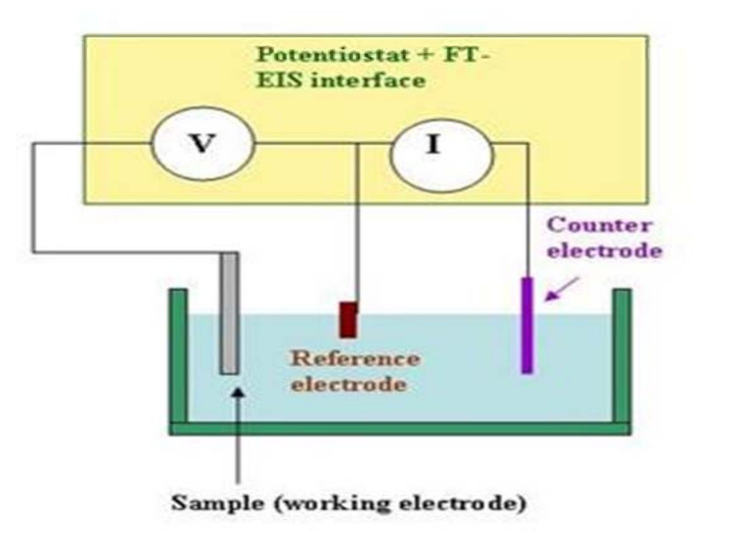


Figure 3.41: Schematic diagram of cell used in cyclic polarization

3.11.4: Procedure for cyclic polarization Test

After the initial setup the software is switched and a new setup is made. The parameters which are set can be obtained from the figure. The various parameters which are of importance have their specific meaning as:

1) **Initial voltage**: Voltage at which scan begins.

2) **Final Voltage**: Voltage at which scan ends.
3) **Scan rate**: the rate at which applied potential changes during the scan.
4) **Conditioning time**: Time required during which specimen is polarized.
5) **Conditioning Voltage**: Voltage required during which specimen is polarized.
6) **Sample Area**: Area Exposed in corrosion environment.
7) **Density**: Density of Coating material.
8) **Equivalent weight**: Equivalent weight of coating material.

The Cell is connected to potentiostat when all parameter are set the run command is given and the process starts. Figure 3.39 -3.41 shows the setup used for the test. The plots of E v/s log I is obtained in monitor in few minutes and the value of E_{corr}, I_{corr} and corrosion rate in mpy unit are calculated by standard software. The values obtained are saved and similarly the next sample is examined.

Table 3.16: Data code for corrosion studies

Sample code	TMAZ region	HAZ region
E1	T1	H1
E2	T2	H2
E3	T3	H3
E4	T4	H4
E5	T5	H5
E6	T6	H6
E7	T7	H7
E8	T8	H8
E9	T9	H9

3.12 INFRARED THERMOGRAPHY

3.12.1 Exploring the Infrared (IR) Thermography for friction stir welding: a unique feature

Infrared thermography was done during the welding at different locations on the weld line. The thermal images and actual image of the welding spot is recorded and spot of max temperature is noted.

Emissivity of Al is considered as 0.95.

3.12.2 Specifications of IR Thermal imaging camera

Model : TH7800 (figure 3.42)

Make : NEC San-ei Instruments, Japan

Specification :

1) Temperature Range : -20°C to 1000°C
2) Accuracy : ± 2% or ± 2°C of reading
3) Resolution : 0.1°C
4) Sensitivity : 1 lux
5) Field of view : 27°±5% (H) × 20.3°±5% (V)
6) Instantaneous Field of View : 1.5 mrad
7) Spectral Band : 8.0 to 14.0 µm
8) Effective image pixels : 752 (H) × 480 (V) pixels
9) Focusing Distance : 50 cm to infinity
10) Image Processing :
    - On-Board Flash Memory : Stores up to 1000 images
    - Software : Included

Figure 3.42: Infrared Thermal Imager Used For Thermography (NEC, Japan)

3.12.3 Specifications of IR Thermal imaging camera

Model : T620 (figure 3.43)

Make : FLIR, Switzerland

Specification :

IR resolution: 640 × 480 pixels

Thermal sensitivity/NETD: <50 mK @ +30°C (+86°F)

Field of view (FOV) / Minimum focus distance: 25° × 19° / 0.25 m (0.82 ft.)

Spatial resolution (IFOV): 0.69 mrad

Image frequency: 30 Hz

Focus: Automatic (one shot) or manual

Zoom: 1–4× continuous, digital zoom, including panning

Focal Plane Array (FPA) / Spectral range: Uncooled microbolometer / 7.5–14 µm

Figure 3.43: IR Thermal imaging camera (FLIR make)