Various tool geometries and base material used to obtain FSW joint using different parameters are discussed in this chapter. Different joints are tested for quality of the welds and evaluated.

**4.1 SELECTION OF TOOL GEOMETRY**

For selecting the friction stir welding tool geometry the thickness of the base plates to be welded is to be selected. The materials required for performing friction stir welding experiment are

1. Base material
2. Tool material

**4.1.1 Base Material**

Although welding is a prominent joining process in terms of fabrication cost, the traditional arc welding methods are not capable of producing sound welds due to metallurgical problems in aluminum alloys. FSW process which was recently invented enables the welding of high performance aluminum alloys that are used in aircraft structures. In many industrial applications, steels are replaced by nonferrous alloys, in most cases by aluminum alloys. Aluminum is an easily saved resource as it can be recycled.
4.1.1.1 Aluminum Alloys

Pure aluminum is a silvery-white metal, light, non-toxic, non-magnetic and non-sparking. It can be easily machined and can be cast. The major alloys of this series include AA6351, AA6061, AA6005 and AA6082. By taking the various applications into consideration 6XXX series aluminum alloys are chosen as the base material.

AA6061, AA6082 and AA6351 is used more in the fabrication of lightweight structures where a high strength-to-weight ratio and good corrosion resistance is required.

4.1.1.2 Properties [49]

Chemical composition, physical properties and mechanical properties of aluminum alloy AA6061, AA6082, AA6351 are given in table 4.1, 4.2, 4.3

<table>
<thead>
<tr>
<th>Elements</th>
<th>Mg</th>
<th>Mn</th>
<th>Fe</th>
<th>Si</th>
<th>Cu</th>
<th>Cr</th>
<th>Zn</th>
<th>Al</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base Metal (AA6061)</td>
<td>1.10</td>
<td>0.12</td>
<td>0.35</td>
<td>0.58</td>
<td>0.22</td>
<td>0.04 - 0.35</td>
<td>--</td>
<td>Balance</td>
</tr>
<tr>
<td>Base Metal (AA6082)</td>
<td>0.66</td>
<td>0.66</td>
<td>0.20</td>
<td>0.81</td>
<td>0.05</td>
<td>0.001</td>
<td>0.03</td>
<td>Balance</td>
</tr>
<tr>
<td>Base Metal (AA6351)</td>
<td>0.586</td>
<td>0.65</td>
<td>0.355</td>
<td>0.90</td>
<td>0.086</td>
<td>--</td>
<td>0.89</td>
<td>Balance</td>
</tr>
</tbody>
</table>

Table 4.1: Chemical composition of AA6061, AA6082, AA6351
<table>
<thead>
<tr>
<th>Physical Property</th>
<th>Density (kg/m³)</th>
<th>Melting Point, deg C</th>
<th>Modulus of Elasticity, GPa</th>
<th>Poission's Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base Metal (6061)</td>
<td>2700</td>
<td>660</td>
<td>69</td>
<td>0.33</td>
</tr>
<tr>
<td>Base Metal (6082)</td>
<td>2700</td>
<td>555</td>
<td>70</td>
<td>0.33</td>
</tr>
<tr>
<td>Base Metal (6351)</td>
<td>2600</td>
<td>600</td>
<td>70</td>
<td>0.33</td>
</tr>
</tbody>
</table>

Table 4.2: Physical Properties of AA6061, AA6082, AA6351

<table>
<thead>
<tr>
<th>Mechanical Property</th>
<th>Yield Stress, MPa</th>
<th>Ultimate Tensile Strength, MPa</th>
<th>Hardness Number</th>
<th>Elongation, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base metal (6061)</td>
<td>276</td>
<td>310</td>
<td>95</td>
<td>12</td>
</tr>
<tr>
<td>Base Metal (6082)</td>
<td>310</td>
<td>340</td>
<td>100</td>
<td>11</td>
</tr>
<tr>
<td>Base Metal (6351)</td>
<td>285</td>
<td>310</td>
<td>95</td>
<td>14</td>
</tr>
</tbody>
</table>

Table 4.3 Mechanical Properties of AA6061, AA6082, AA6351

4.1.2 Tool Material

FSW process requires a tool of harder material than the work piece material. When selecting a material for use as a FSW tool, design must be done with setting maximum loads on the tool, high operating temperatures and the required wear resistance. Loads on the tool can be several kilo Newton (kN). Stress analysis should be performed to ensure
proper design as undersized tools can fail at the time of operation. The failures could include the pin breaking and remaining back in the weld joint, or the tool fracturing above its shoulder and being ejected from its holder. To reduce the likelihood of failure, the tool material must have high yield strength. The tool must also be able to withstand the required temperatures to heat the work piece material to a level just below its melting point. The tool material selected to weld aluminum must be able to maintain its shape and function near the elevated temperature i.e. melting point of aluminum (660°C). The properties of metals change with temperature, and hence attention must be paid to both the yield strength and the operating temperature of the tool. An additional characteristic of concern is resistance to wear of tool. As the tool has to plastically deform another metal, it must be able to have a high resistance to wear.

### 4.1.2.1 Tool Material Characteristics

Production of a quality friction stir weld joints requires a proper tool material. Various tool material characteristics are:

- **Ambient and elevated temperature strength**

  The tool material must be able to withstand the compressive loads when the tool first comes into contact with the work piece and have sufficient compressive and shear strength at elevated temperature to prevent tool fracture or distortion for the duration of the FSW process.
• **Elevated temperature stability**

In addition to sufficient strength at elevated temperatures, the tool must maintain strength and dimensional stability during the time of process. Poor creep resistance would change the tool dimensions during welding.

• **Wear resistance**

Excessive tool wear changes the tool shape, thus changing the weld quality. The probability of defects increases. In friction stirring process, tool wear can occur by adhesive, abrasive or chemical wear mechanisms.

• **Tool reactivity**

The reactivity of tool materials with work piece or the environment should be minimum as it would change the surface properties of the tool.

• **Fracture Toughness**

Tool fracture toughness plays a significant role during the tool plunge and dwell. The local stresses and strains produced when the tool first touches the work piece may break the tool.

• **Machinability**

Many FSW tools are designed with features that must be machined and ground to make it into the tool shape. Any material
that cannot be processed to the required tool design should not be considered.

- **Uniformity in Microstructure and density**

  Tool materials are not useful if there are local variations in microstructure or density. A weak region within the tool is where premature fracture occurs. FSW tools should only be manufactured from dense grade materials.

### 4.1.2.2 Materials used for Tools

Most common materials used for tools are HCHC and H13 as they exhibit high yield strengths and toughness. They are used in processes where large loading, high temperature and frictional contact occur. The materials used for tools include easy availability and machinability, low cost and established material characteristics. Hot-worked steels (group H) have been developed to withstand the combinations of heat, pressure and abrasion associated during such operations. H steels are divided into three subgroups:

- H10 to H19 – Chromium hot worked steels
- H21 to H26 – Tungsten hot worked steels
- H42, H43 – Molybdenum hot worked steels

H10 to H19 have good resistance to heat softening and hence H13 tool is used in the present work, as their toughness at the normal
working hardness is 40 to 55 HRC. H13 has the best properties to withstand the operating conditions of FSW. AISI H13 is chromium molybdenum hot worked air hardening steel and is known for its good elevated temperature strength, thermal fatigue resistance and wear resistance.

### 4.1.2.3 Properties of H13

Properties of H13 tool steel are given below:

<table>
<thead>
<tr>
<th>Elements</th>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>Cr</th>
<th>Ni</th>
<th>Mo</th>
<th>V</th>
<th>Cu</th>
<th>P</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tool Material (H13)</td>
<td>0.35</td>
<td>0.30</td>
<td>0.88</td>
<td>5.0</td>
<td>0.3</td>
<td>1.5</td>
<td>1.0</td>
<td>0.25</td>
<td>0.03</td>
<td>0.03</td>
</tr>
</tbody>
</table>

Table 4.4: Chemical composition of H13

<table>
<thead>
<tr>
<th>Physical Property</th>
<th>Density (kg/m³)</th>
<th>Melting Point, °C</th>
<th>Modulus of Elasticity, GPa</th>
<th>Poisson’s Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tool Material (H13)</td>
<td>7850</td>
<td>2600</td>
<td>200</td>
<td>0.27 – 0.3</td>
</tr>
</tbody>
</table>

Table 4.5: Physical Properties of H13

<table>
<thead>
<tr>
<th>Mechanical Property</th>
<th>Yield Stress, MPa</th>
<th>Allowable Shear Strength, MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tool Material (H13)</td>
<td>415</td>
<td>250</td>
</tr>
</tbody>
</table>

Table 4.6: Mechanical Properties of H13

<table>
<thead>
<tr>
<th>Thermal Property</th>
<th>Thermal Conductivity, W/mK</th>
<th>Thermal Capacity, J/KgK</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tool Material (H13)</td>
<td>24.3</td>
<td>460</td>
</tr>
</tbody>
</table>

Table 4.7: Thermal Properties of H13
Fig. 4.1 Tool Material and Machine used for FSW Process

Fig. 4.1.1 Fixture used in the experimental work
4.2 FSW TOOL GEOMETRY

The quality of weld can be improved by selecting the best tool in terms of design, made of sufficiently strong, tough and hard wearing tool material. To minimize the heat loss and damage caused to the machinery, the tool should have oxidation resistance and low thermal conductivity. For welding aluminum alloys up to 50mm thick plates, H13 hot worked tool steel is acceptable. A specially designed tool can be used for plates of higher thickness. The Triflute and Trivex series are advanced designs that cause a good stirring of the material around the tool. Less forces act on the tool during the welding process when the Trivex tool is used. A concave shoulder profile is preferred more as the material displaced by the tool is escaped and extrusion of material from shoulder is prevented [50]. The tool geometry governs the traverse rate at which the welding is done.

The tool has two primary functions:

(a) Localized heating, and

(b) Material flow

A properly designed tool is the important component in the whole process, in which the essential parts are the tool pin and shoulder (Ref. Fig. 4.2). The profiled pin called probe is the extension along the axis of rotation and the shoulder is the working surface of the tool, normal to axis of rotation which will be in contact at the point along the joint line.
Due to the friction between pin and work piece primary heating is generated and later additional heating is generated from deformation of the material. The process of plunging of tool is done till the shoulder touches the work piece. The biggest component of heating occurs due to the friction between the shoulder and work piece. The size of pin and shoulder are important from the heating aspect. The second function of the tool is to stir and move the material. The design of tool governs the uniformity of microstructure and the process parameters. To alter material flow, mixing and to reduce process loads, the modifications in tool are carried out.

![Fig 4.2 Nomenclature of FSW Tool](image)

**4.2.1 Various Forces Acting On the Tool**

During welding, a number of forces will act on the tool. A downward force is required to maintain the position of the tool at the line of joining. The traverse force acts parallel to the tool motion and is along the traverse direction. Since this force arises as a result of the resistance
of the material to the motion of the tool, this force will decrease as the temperature of the material around the tool is increased. Torque is required to rotate the tool. To avoid wear and tear on the tool, the welding cycle should be modified so that the forces acting on the tool are as low as possible. Kovacevic et al [51] observed that axial force is directly responsible for the plunge depth of the tool pin into the work piece and load characteristics associated with linear friction stir weld.

4.2.2 Tool Geometry

Based on the literature survey, the tool geometry is as per the thickness of the base plates. The diameter of the pin is equal to the thickness of the parts to be welded and its length is slightly shorter than the thickness of the part. Tool shoulder-to-pin diameter ratios play an important role in stir zone development [4]. Tools with shoulder-to-pin diameter ratios close to 1 (one) do not produce a TMAZ, and do not adequately preheat and soften the material before the tool advances. Tools with very large shoulder-to-pin diameter ratios may preheat and soften too much the material, resulting in the material not sticking to the pin. The joints fabricated by the tools with shoulder-to-pin diameter ratios \((D/d)\) of 3 produced higher tensile strength and elongation [5] compared to that fabricated using the tools with \((D/d)\) values of 2.5 and 3.5. The base plate chosen for this investigation is AA6061, AA6082 and AA6351. The thickness of the plate and the tool dimensions are: Tool pin
diameter \(d\) = 6 mm, Tool pin length \(h\) = 5.6 mm, Tool shoulder diameter \(D\) = 18 mm. These dimensions are chosen as per the procedure suggested by Balasubramanian et al [5].

The five profiles (cylindrical, tapered cylindrical, threaded cylindrical, square and triangular) which are considered for the tool pin are shown below in Fig.4.3 and are used for the experimental work. The design of pin and shoulder are important as it is required to retain in the weld cavity the maximum amount of material that is transferred.

Fig.4.3 Schematic representation of line diagrams of FSW Tools
Fig. 4.3.1. Straight cylindrical profiled tool

Fig. 4.3.2 Tapered profiled tool

Fig. 4.3.3 Threaded cylindrical profiled tool
4.3 DOE FOR OPTIMIZING FSW PARAMETERS

The DOE is an experimental strategy in which effects of multiple factors are studied simultaneously by running tests at various levels of the factors. The levels to be taken, combination of levels, and the number of experiments to be run are given in DOE [52, 64].

Guidelines for Designing an Experiment [53]

1. Recognition and statement of the problem
2. Choice of the factors, levels and ranges
3. Selection of the response variable
4. Choice of the experimental design
5. Performing the experiment
6. Statistical analysis of the data
7. Conclusions and recommendations

**Working limits of parameters:** The quality of the FSW joint obtained is based on many process parameters. The parameters which have an effect on the joint are as listed below:

1. Material
   i. Thickness
   ii. Alloy Composition

2. Action of Forces
   i. Axial Force with which the tool acts
   ii. Force with which the tools are held

3. Tool
   i. Spindle rotational speed
   ii. Tool geometry
   iii. Tool material

4. Welding speed/Feed rate

5. Plunge time etc.,
Among the listed parameters a few parameters have major effect on the quality of the joint obtained by FSW such as the axial force (F), Tool rotational speed (TRS), Tool profile (T) and Weld speed (WS). Trial experiments are carried out using 6mm thick rolled plates of aluminum alloys with varying tool rotational speed, welding speed, axial force and different tools, and experiments are conducted on different aluminum alloys. The trial runs are carried out by varying the different parameters. The range of the different process parameters are arrived at on inspection of the obtained joints. The variation in the tool rotational speed has effect on the weld quality. As the tool rotational speed increases, it becomes easier for the penetration of the tool, and also it is responsible for the material mixing rate. The amount of heat to be generated is affected by the weld speed or feed. Due to the slow weld speed, the coarse grains are formed inside the weld as the heat generated is acted at one point only. The reason for increase in heat is more time of contact of tool with the work piece. On the other hand higher weld speed will resist the motion of tool between the two plates, and therefore less heat is generated. As, the relationship among the parameters like tool rotational speed, weld speed and the heat generated is complex, the selection of the parameters should be done optimally to obtain good quality weld. To obtain a quality weld, extensive plastic flow is required, and the forces acting on the tool are to be minimized. To achieve this, the material surrounding the tool should be hot enough. Otherwise defects may occur at the weld or the
tool may break. If there is excessive heat flow, the final properties of the weld may get affected. Due to such type of conflicting demands, the concept of processing window is introduced, i.e., the range of processing parameters that produces a good quality welds are to be obtained. When the tool rotational speed is below 1000rpm, a wormhole was observed, and when tool rotational speed is above 1200 rpm, tunnel defect was detected. The size of the top region increases, because a cavity is formed in the bottom region of the stir zone. The former may be due to insufficient heat generation, and the latter may be due to excessive turbulence because of the high rotational speed. When welding speed was lower as there is excessive heat generated per unit length, at higher weld speed, due to insufficient heat input, the joints resulted in visible defects. Due to insufficient downward force, defects were visible at the joint and due to higher downward force excessive thinning was observed. Pinhole defects were observed when the axial force applied was low i.e less than 3kN and the reason for their occurrence is absence of vertical flow of material. When the axial force applied is high, due to the high heat input tunnel defects were observed.

Therefore, finding the ranges for the process parameters is very important for conducting the DOE as the experiments are conducted within the working limits. To find the limits, a number of trail runs are carried out and with different combinations. Based on the quality of the joint obtained, the working limits are finalized.
On analysis among the five tools with different geometries, three tools namely Tapered Cylindrical, Threaded Cylindrical and Square pin produced joints with better mechanical properties than the other two profiled tools i.e straight cylindrical tool and triangular tool (Fig. 4.3.1, 4.3.5). In addition, the square pin profiles produce a pulsating stirring action in material flow. Elangovan et al [14] in their study found that the welded joints obtained by using square pin profiled tool with shoulder diameter 18mm are superior to the other joints. For 6mm thick AA6061, AA6082, AA6351 with different tool geometries, the limits considered for experimentation is as mentioned in Table.4.8.

<table>
<thead>
<tr>
<th>Process Parameters</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tool Rotational Speed (TRS)</td>
<td>1000-1200 (rpm)</td>
</tr>
<tr>
<td>Welding Speed (WS)</td>
<td>45-75(mm/min)</td>
</tr>
<tr>
<td>Tool Profile (T)</td>
<td>3 tools</td>
</tr>
<tr>
<td>Axial Force (F)</td>
<td>4-6 kN</td>
</tr>
</tbody>
</table>

Table.4.8 Experimental limits considered

4.4 MODIFIED TOOL

The heat generated by the rotating tool softens the material in the vicinity of the tool. The tool pin shears the material to its backside during FSW process to plastic state. The material undergoes intense plastic deformation around the tool.
The pin driven flow yields onion rings structure which is caused by the flux of layers of plasticized material around the pin. This flow is predominant in determining the characteristics of the nugget of the welds. Profile of the pin regulates the welding speed of the tool, and hence plays a crucial role. As Colegrove and Schercliff [48] explained, the shoulder is the source of frictional heat and it prevents the material from flowing out of the weld cavity. During the time of tool plunge, a cavity is created in the base material and the pin profile decides the shape of the cavity. There is plasticized material around the pin and below the shoulder at this stage. An onion ring structure is caused by the flux of layers of plasticized material around the pin.

When the tool is traversed, the material from the leading edge is progressively plasticized and flows to the trailing edge through the retreating side by shoulder and pin driven flows [54]. The shoulder driven material forges against the advancing side flowing from the retreating side. The layers are stacked in the line of weld which is formed around the pin by the driven material flow. A part of material transferred is lost as flash. Flash is formed if the material to transfer to trailing edge is more than the material flowing out from cavity. The flash formation leads to insufficient material filling in the advancing side. The formation of defects like grooves or voids is due to the insufficient material to fill the cavity. Excessive flash is formed and other defects like groove, tunnel
and cavity were observed and the formation of these defects are due to either excessive or less heat input, or abnormal stirring [5].

To avoid the flash formation, a modified tool is proposed in the present work. A cavity at the end of the shoulder (at the starting point of the tip) is provided, such that at the time of stirring process, the material flow is optimal and results in proper stirring of the material [63]. (Refer Fig. 4.4 a, 4.4 b). During the stirring process the plasticized material flow between the tool and the base material makes the base material relatively cooler than the material in the groove. If the resistance of the base metal to the tool force which depends on the plasticized material is high, the material may flow out of the weld cavity. The material which gets ejected from the weld cavity has to be retained in the cavity, so that a strong bond is formed. For this purpose, a undercut is provided at the tip-tool interface in the modified tool to facilitate the retention of the plasticized material in the weld cavity.
4.5 SELECTION OF ORTHOGONAL ARRAY (OA)

Selection of an Orthogonal Array is an important stage in conducting the Design of Experiments (DOE). The number of parameters and interactions, and the number of levels of the parameters are the points which are to be considered before using an Orthogonal Array (OA). To analyze the non-linear behavior of the parameters, the levels of the parameters should be more than two. Four parameters at three levels each are selected for conduct of DOE. As per Taguchi method, the total degrees of freedom (DOF) of selected OA must be greater than or equal to the total DOF required for the experiment, and hence L9 OA is selected. The trials are repeated two times for determining the adequacy of mathematical models. Thus a total of 18 trials were performed. After obtaining the weld joints, they are cut into the samples of required dimensions for obtaining the mechanical properties. The welding experiments are carried out by design matrix Mechanical properties like tensile strength, yield strength, percentage elongation and hardness are increased for the welded plates, and the results are analyzed. The Table 4.9 shows the process parameters and levels of the parameters considered for the experimentation.
<table>
<thead>
<tr>
<th>Variables</th>
<th>Level 1</th>
<th>Level 2</th>
<th>Level 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tool Geometry (T)</td>
<td>Tapered Cylindrical</td>
<td>Threaded Cylindrical</td>
<td>Square Profiled</td>
</tr>
<tr>
<td>Tool Rotational Speed, TRS (rpm)</td>
<td>1000</td>
<td>1100</td>
<td>1200</td>
</tr>
<tr>
<td>Welding Speed, WS (mm/min)</td>
<td>45</td>
<td>60</td>
<td>75</td>
</tr>
<tr>
<td>Axial Force, F (KN)</td>
<td>4</td>
<td>5</td>
<td>6</td>
</tr>
</tbody>
</table>

Table 4.9 Process Parameters and levels of design factors

4.6 S/N RATIO (Signal – To- Noise Ratio) ANALYSIS

The signals are indicators of the effect on average responses, and the noises are measures of the influence on the deviations from the sensitiveness of the experiment output to the noise factors. The deviation of quality characteristics from the derived value is determined by the S/N ratio. To analyze the influence of the factors on the responses, the Signal–To-Noise (S/N) ratio for each factor is calculated. The S/N ratio is chosen according to the larger-the-better criterion as it is required to maximize the output response [55]. The tensile strength is the measured output in the present study to study the effect of process parameters of FSW.
\[ \eta_{ij} = -10 \log \left( \frac{1}{n} \sum Y_{ijk}^2 \right) \quad \ldots \ldots 1 \]

where, \( n \) is number of tests and \( Y_{ij} \) is experimental value of the \( i^{th} \) quality characteristics in the \( j^{th} \) experiment

The arithmetic means and S/N ratio of different parameters are calculated and represented against each experiment number. As it is larger-the-better criterion, the highest S/N ratio obtained is the optimum combination of process parameters [62].

The DOE helps in identifying the different parameters which affect the output. Among many experiments conducted, identifying the parameters having prominence is a major task. On identifying the parameters to analyze the results obtained is a stage where an optimal decision is to be taken. S/N ratios with larger the better criteria is calculated to obtaining the results and to analyze.

A modified tool with undercut at the tip-tool is made. The undercut at the tip tool interface facilitates the retention of the plasticized material in the weld cavity. Experiments are conducted with both existing tool and modified tool. Using both existing tool and modified tool, the mechanical properties of weld joints are obtained with optimal parameters obtained using DOE.