To join butt and lap joints, Friction Stir Welding which is a solid state process is used. The FSW is a recent technique invented in 1991 by TWI (The welding Institute) and is being used to weld aluminum alloys of different series which were difficult to weld and hence were restricted to limited use. Due to non melting and re-solidification of metal, distortion was low and the weld is free of porosity.

![Fig. 3.1 Schematic diagram of friction stir welding process](image)

A non consumable, rotating tool is brought into contact with the plates to be joined. As the tool moves along the joining surface the heat is generated and below the solidous temperature [47, 48], the joints are formed. When the shoulder comes into contact with the surface of plates, the temperature increases due to heat generated and the pin of the shoulder stirs in the joining surface allowing flowing of the material
backside of the pin. As the tool passes, the metal cools and a processed zone is produced.

A tool made of harder material than the plates to be joined is used. Earlier the aluminum alloys, zinc, magnesium and other soft materials were joined using FSW. Presently the use of FSW process is extended to join materials with high temperatures, as the harder tools are being developed.

3.1 STAGES OF FSW PROCESS

FSW cycle mainly consists of four stages.

1. Plunge Stage
2. Dwell Stage
3. Welding Stage
4. Pull out Stage

![Fig 3.2 Stages of friction stir welding process](image)
3.2 MICROSTRUCTURE FEATURES OF FRICTION STIR WELDS

The solid state nature of the FSW process produces microstructures with high characteristics. The first attempt at classifying microstructures was made by P L Threadgill. This has been developed at TWI and has been discussed with a number of appropriate people in industry and academia and has also been provisionally accepted by the Friction Stir Welding Licenses Association. The system divides the weld zone into distinct regions and is as shown in Fig 3.4 and 3.5.

![Fig 3.4 Different zones of FSW joint at the weld.](image)

- a. Unaffected material or parent material
- b. Heat Affected Zone (HAZ)
- c. Thermo-Mechanically Affected Zone (TMAZ)
- d. Weld Nugget (WN)
3.3 PARAMETERS

- **Tool**

  The rotating device between the machine spindle and the work piece is referred to as the ‘tool’. The part which creates stirring action is referred to as the ‘pin’. The part of the tool, which is pressed on to the surface of the work piece during welding is referred to as ‘shoulder’.

- **Leading Edge and Trailing Edge**

  In a non-cylindrical tool the terms ‘leading edge’ (front face of the shoulder during welding) and ‘trailing edge’ (rear face of the shoulder during welding) are used, where as in cylindrical profiled
tools there is clearly no edge and so the terms ‘leading face’ and ‘trailing face’ may be preferred. ‘Pin leading face’ is the front face of the pin during welding. Similarly ‘Pin trailing face’ is the rear face of the pin during welding.

- **Advancing side and Retreating side**

  The side of the weld where the direction is same as the direction of rotation of shoulder is called the ‘Advancing Side’ (AS) and where the direction is opposite to direction of rotation of shoulder is called the ‘Retreating Side’ (RS) (Fig. 3.6). The total area of the tool on the work piece surface is described as the ‘tool shoulder footprint’.

  ![Fig. 3.6 Representation of Advancing and Retreating side due to rotation of tool](image)

- **Forces**

  Due to the force applied downward and due to the force with which the two plates to be joined are kept in contact at the time of process are important in FSW process. The force applied parallel to the axis of the rotation of the tool (Z-direction) is the ‘down force’.
The force applied parallel to the welding direction (X-direction) is the ‘traversing force’.

- **Welding speed and Rotational speed**

  The term ‘welding speed’ is referred to travelling speed or traversing speed, which is the rate of travel of tool along line of joint. ‘Tool Rotational Speed’ is the speed at which the friction stir welding tool rotates.

### 3.4 DEFECTS FOUND IN FSW JOINTS

The FSW which is a solid state welding process also produces several types of defects. They may be due to improper processing conditions and material flow problems inside the die cavity. The processing parameters can lead to either hot or cold processing conditions which in turn increase the occurrence of defects due to improper flow of the metal. In addition, an improper axial force can create defects regardless of the hot or cold conditions. The most common defect found in FSW known as void or worm hole is due to lack of consolidation of the material inside the weld nugget. It is caused by cold processing conditions due to the combination of traverse speed and tool rotation or it may be caused by insufficient axial force. The insufficient refilling of the advancing side of the nugget is due to the two conditions. Porosity tends to form very close to the pin and on the advancing side. The wormholes and voids can be
minimized by increasing the axial force of the FSW tool by increasing plunge depth and by increasing the heating inside the die cavity. Increase in the heat, axial force will cause the metal to become softer and collapse the voids.

In the visual inspection of the FS welded joints, several types of defects were observed. A surface-open tunnel was found as a result of insufficient downward pressure. Excessive lateral flash was observed underneath shoulder which was due to outflow of the plasticized material. Other defects like pinhole, piping defect, kissing bond cracks etc, due to improper flow of metal and insufficient consolidation of metals in FSW region as shown in Fig. 3.7.1 & 3.7.2 are found to occur in FSW joints.

Fig 3.7.1 Weld failures due to insufficient downward pressure
Fig 3.7.2 Failure due to increase in downward pressure

For some of the welds no flaw or defect was detected on the weld. In the visual observation of the weld presented, it is clearly seen that a sound joint was obtained as shown in Fig. 3.7.3. In the present study an attempt is made to minimize the defects observed by conducting experiments with a modified tool which has a cavity at the end of the shoulder and also by identifying the optimal axial force in addition to the optimal values of tool rotational speed and weld speed.

Fig 3.7.3 Sound FSW Joint
3.5 ADVANTAGES AND DISADVANTAGES

The main advantage of FSW over traditional welding processes is that no melting of the work piece material takes place. A few other advantages of FSW include:

- Due to absence of melting of material the defects like porosity and voids are less.
- Low distortion and residual stresses in resultant welded zone.
- Higher mechanical properties like ultimate tensile strength, yield strength and hardness.
- Absence of toxic fumes and radiation make it a very environmental friendly process.
- Improved safety due to the absence of toxic fumes or the spatter
- No consumables – conventional steel tools can weld over 1000 m of aluminum and no filler or gas shielding is required for joining of aluminum.
- Easily automated on simple milling machines, lower setup costs and less training required.
- Can operate in all positions (horizontal, vertical, etc), as there is no weld pool.
- Generally good weld appearance and minimal under over-matching, thus reducing the need for expensive machining after welding.
There are few disadvantages associated with FSW process:

- Clamping of the work-piece is a very important criterion in the process.
- Weld speeds are slower which result in longer processing times.
- Surface thickness is reduced marginally during the process as no filler material is involved.
- If the plates are not clamped properly, due to the tool speed and axial force acting, there is possibility of breaking of the tool tip and the tip getting stuck in the weld zone.
- When the tool is retrieved back an exit hole is left behind Fig. 3.8.

![Fig 3.8 FSW Joint with exit hole](image)

**3.6 APPLICATIONS**

The FSW process is suitable for welding plates, pipes or fabrications of complex shape. Applications of the FSW include various industries including a few of the following:
• Shipbuilding and Marine Industries

FSW is suitable for many applications under shipbuilding such as manufacturing of hulls and superstructures, panel for decks, sides, bulk head of floors, aluminum extrusions, offshore accommodation sides, helicopters landing platforms, marine and transport structures, masts and booms and refrigeration plant.

• Aerospace Industry

FSW is being used to weld prototype and production parts in aerospace industries and for fuel tanks in space vehicles. The FSW process can be considered for wings, fuselage, cryogenic fuel tanks, external throw away tanks for military aircraft, repair of MIG welds and various primary and secondary structural joints.

• Railway Industry

The applications of FSW in railway industries include building of container bodies, railway tankers etc.

• Land Transportation

FSW is currently being used by many automotive companies for various applications that include but not limited to building of engine chassis, wheel rims, truck bodies, mobile cranes, body frames etc., and for welding steels the FSW process is feasible as it produces welds with less distortion and good mechanical properties.
• Other Industry Sectors:

FSW is used in welding space frames, fuel tanks, repair of aluminum cars, engine and chassis cradles, wheel rims, cranes, caravans, motor cycle and bicycle frames, articulated lifts and personnel bridges. It can be used for electrical motor housing, refrigeration panels, cooking equipments and kitchens, connecting of aluminum or copper coils in rolling mills.

This is mainly due to the absence of the problems associated with heating the material to its liquid phase followed by the rapid cooling. Issues such as porosity, solute redistribution, solidification are not observed during FSW.

The process parameters are very few to control in FSW. In a fusion weld, there are many process parameters that must be controlled such as shielding gas, purge gas, wire feed rate, voltage and amperage, travel speed, etc. The increase in joint strength combined with the reduction in process variability provides high degree of reliability. FSW has been found to produce high quality welds with a low occurrence of defects.

However, some limitations of the process have been identified. FSW is associated with defects that are unique, for example with insufficient weld temperatures caused by low or high weld speed, the weld material is unable to accommodate the extensive plastic deformation
during welding. Some of the typical factors which are to be considered while selecting this technique are:

- Exit hole left when tool is withdrawn and hence the need of special tooling/techniques to avoid the formation of exit hole in circumferential welds.

- Axial force acting in the downward direction is more and hence, clamping is necessary to hold the plates together.

- Less flexible than manual and arc welding processes.

- The welding rate is less than some fusion welding techniques.

A relatively new technique, Friction stir welding (FSW) is a systematically developed technique for joining aluminum alloys. It is proving to be far more fetching to use FSW than arc welding techniques and can consistently produce long welds, especially between extrusions of high quality and with very low distortion. Consistent with the more conventional methods of friction welding, the weld is made in the solid phase and the major advantage is that there is no melting. The process has received world-wide attention and today many companies are using the technology in production, particularly for joining aluminum alloys. Since FSW is a solid state welding process, it is best suited for welding of materials and is opted in this work.