1.1 Overview

Solid State Welding is defined as the operation of joining two materials by applied pressure providing intimate contact between them and temperature must be lower than the melting point of the base material. The bonding of the materials is the product of the diffusion atoms from their interface [1]. FSW was detected in the welding institute (TWI) of UK in 1991 [2]. Friction stir welding (FSW) has many features such as welded aluminium alloys that difficult welded it by using tradition welding methods, lower voids and defects, used easy, environmentally friendly process and high welding efficiency compared with the fusion welding [3].

Friction Stir Processing (FSP) considers as a solid – state welding process which firstly utilized in 1999 by Mishra et al [4]. FSP is an emerging surface engineering technology depends on the principles of Friction Stir Welding. FSP worked on reduce inherent defects in the base material and locally refines microstructures and also enhance its ductility, formability, fatigue resistance, corrosion resistance, and other properties [5]. Basically, FSP is a local thermo-mechanical metal working process, the change in the properties occurs only in local properties without affecting properties of the remaining structure [6].

Aluminium alloys are separated into two kinds: wrought and cast alloys, and it's subdivided into two types of non-heat-treatable and heat treatable. The heat-treatable aluminium alloys have good toughness and strength as well as maintaining the corrosion resistance and low density of aluminium [7]. The most of aluminium alloys are welded by the fusion welding such as Metal inert gas (MIG) and Tungsten inert gas (TIG) but many problems and difficulties happen in fusion welding of these aluminium alloys such as (porosity, cracks, and oxide inclusion) and these defects cause welding poor [8].

Taguchi method was performed utilizing the MINITAB 18 program, which involves analysis of variance (ANOVA) and the single to noise (S/N ratio). It's an appropriate problem-solving tool, which is utilized to enhance the performance of a process/product or a system without doing a large number of experiments. This reduces the cost of experimentation and saves time. Taguchi method is utilized to find more parameters effect within the parameter combinations, by using the S/N and ANOVA. It is utilized as the statistical design of experiment (DOE) to optimize parameters of welding operation such as pin geometry, rotation speed, and welding speed. The optimization operation depends on the influence of welding parameters on ultimate stress [9].

The finite element method is a numerical method that used to get a solution for many engineering problems. Transient, Steady, linear, or nonlinear problems in stress analysis, fluid flow, heat transfer, and electromagnetism. Today, ANSYS is utilized in numerous engineering fields, such as aerospace, automotive, nuclear, and electronics [10].

1.2 Friction Stir Welding

Friction stir welding (FSW), detected by The Welding Institute, the UK in 1991 is considered a solid-state joining operation due to no material melting happens during the welding operation and the material joined by the plastic deformation and locally frictional heat [2]. In FSW, the two work-pieces were firmly clamped onto the worktable to avoid vibration or moving it [11]. To start the welding operation, the pin rotates at a specific speed and then plunges into the line interface between the two work-pieces. The heat is generated from the friction between the welded materials and non-consumable tool, and the weld material rising to a relative steady-state temperature and becomes plasticized. The tool is moved along a predefined weld path when plasticized state is reached. The material in the weld zone remove from the pin entering and travelling during the part try to extrude out of the pinhole but is kept in place by the shoulder [12].

The heat generated is reached to 70 - 90% from the melting point for the material and its causes soften in weld zones and permits moving the tool along the interface line between two faces. From the advance side, the plasticized material is transferred to the retreating and it leaves a solid phase bond between the two pieces, FSW and FSP are presented in figures **(1.1**) and (**1.2**) respectivily [13].

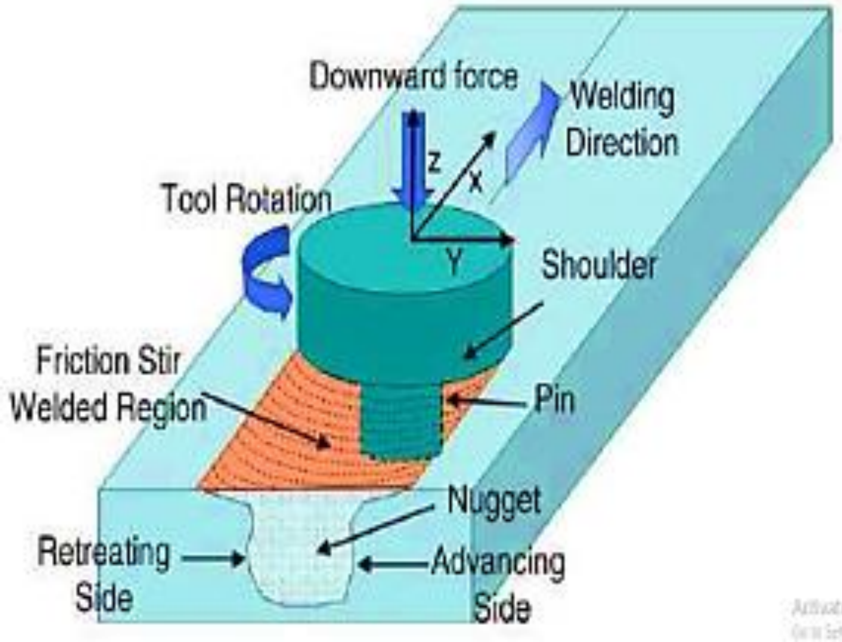

Figure (**1.1**): FSW for weldment [14].

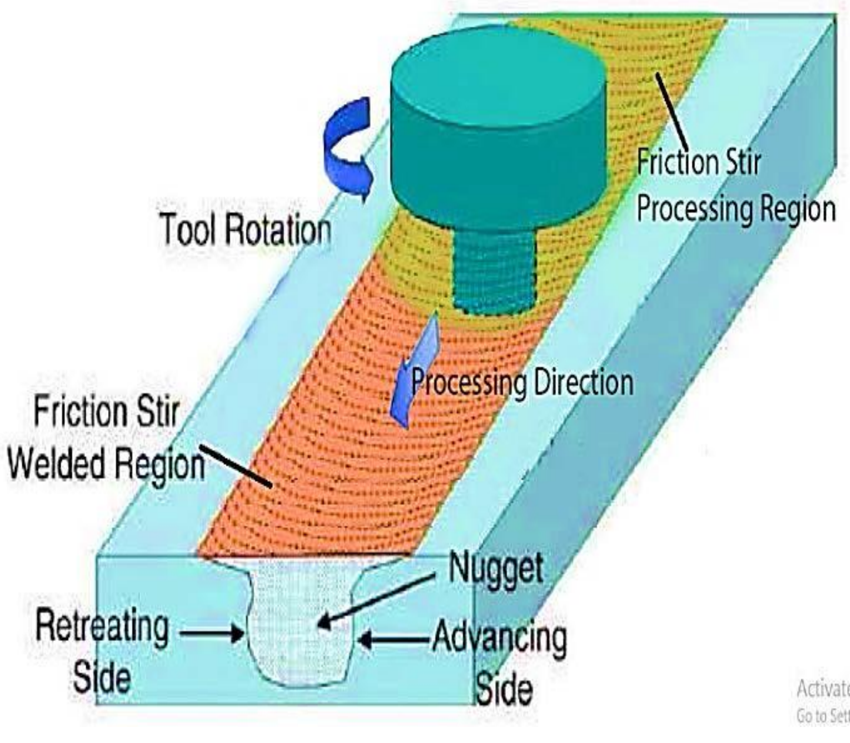

Figure (**1.2**): FSP for weldment [14].

1.2.1 Friction Stir Weld Zones

The welding zones are divided into three main zones as shown in figure **(1.3)**:

A. The stir zone (SZ) (also called the dynamically recrystallized, the nugget zone(NZ)) is the zone that occurs in it heavily deformed material that roughly corresponds to the location of the pin through the welding. In stir zone, the grains are roughly equiaxed and it smaller than the grain in the base material [15].

B. The thermo-mechanically affected zone (TMAZ) takes place on both sides of the nugget zone. In this zone, the temperature and strain are lower and the influence of welding on the microstructure is smaller. Unlike in the nugget zone, the microstructure is recognizabe in the base material with significant rotation and deformation. Although the term TMAZ technically defines to the entire deformed zone, it is often utilized to define any zone not already covered by the terms flow arm and stir zone [15].

C. The 'heat affected zone' (HAZ) is common to all welding operations. Although the HAZ zone is exposed to a thermal cycle, it's not deformed through the welding operation. HAZ has a lower temperature from the TMAZ but may still have an important influence if the microstructure is thermally unstable. Actually, in age-hardened aluminium alloys, this zone usually has mechanical properties considered poorest [15].

Rotation the tool in clockwise and moving the welding plates on long welding line with specified feed rate (welding speed) work on create to side for weldment, Advance side (AS) which its direction of stir operation parallel to feed rate while retreating side (RS) is located in the opposite side as shown in figure **(1.4)** [16].

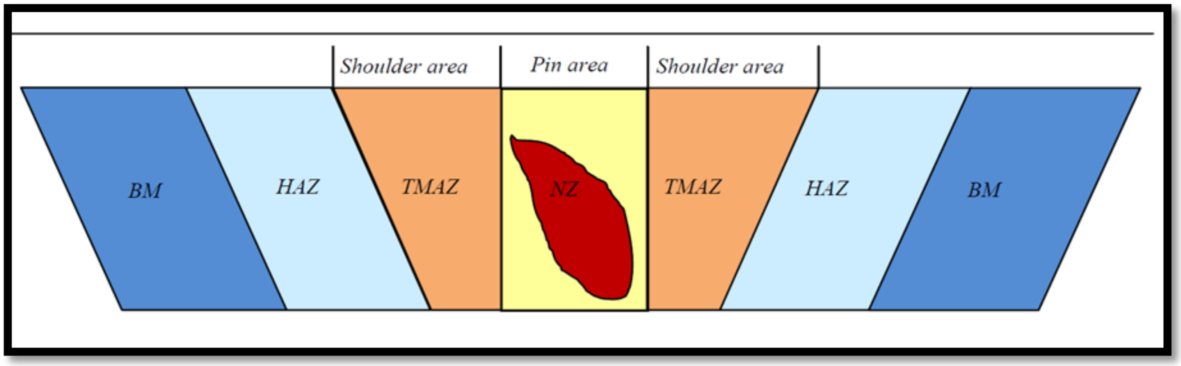

Figure **(1.3)**: Welding zones for FSW process [17].

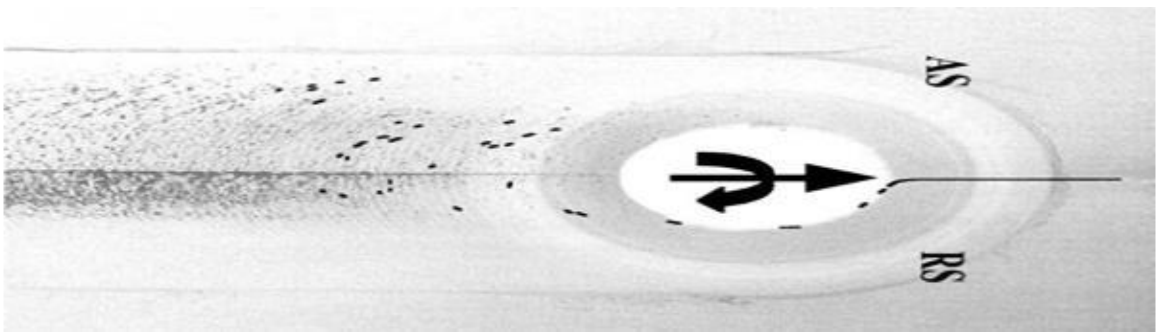

Figure **(1.4)**: Advance and Retreating sides for weldment [16].

1.2.2 Tool Material and Geometry

The geometry of the tool is the most influential development and it's very important in material flow and in turn, governs the traverse rate at which FSW can be conducted. The FSW tool involves a pin and a shoulder as shown in figure **(1.5)**. The tool has dual main functions: (a) material flow and (b) localized heating. In the first step of tool plunge, the heating products primarily due to the friction between work-piece and the pin as well as some heating addition products from the deformation of the material. The tool is continuing in plunged until the shoulder become in touch with the work-piece. The friction between the work-piece and the tool production higher component of heating. From the heating aspect, the relative size of the shoulder and pin is important, and the other design features are not critical. The shoulder also provides confinement for the heated volume of material. The other tool function is to ‘move’ and ‘stir’ the material. The uniformity of properties and microstructure in addition to the process loads are governed by the tool design. Commonly welding tools are explained in figure (1.5) [18].

The tool material of the FSW must be chosen carefully. The quality of the wear and welding resistance for the tool must be taken in the account when chosen the material of the tool and the table **(1.1)** explained the suitable material tool. The material of the tool has a direct impact on the weld quality due to their influence on the generation rates and heat dissipation. Besides, corrosion in the tool material has dramatic adverse impacts on both the rising friction stir welding cost and weld microstructure [19].

Table **(1.1)** FSW Tool materials and thickness [20].

Alloys to be welded	Thickness (mm)	Tool material
Copper	3-50	Ni-alloys-alloys, PCBN, Tool Steels
Stainless steels	3-10	W-alloys, PCBN
Aluminium	3-50	Tool steels, Co-WC Composite
Nickel	3-10	PCBN
Low-alloy steels	3-10	WC composite, PCBN
Magnesium	3-10	Tool steel, WC Composite
Titanium	3-10	W-alloys

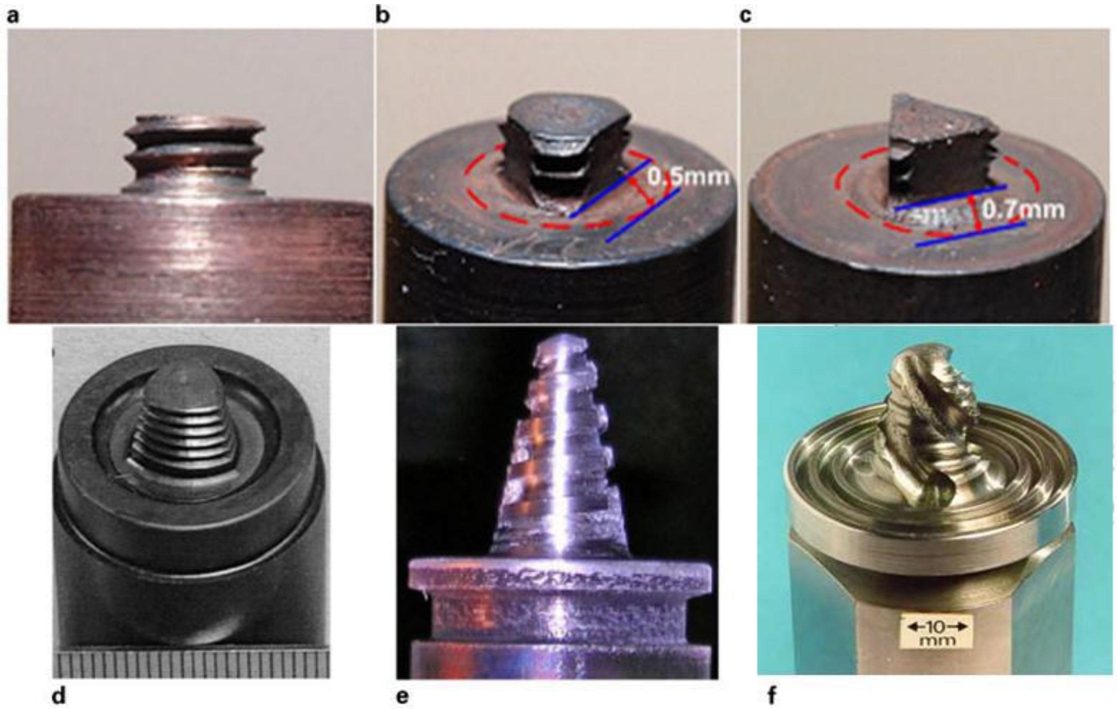

Figure **(1.5)**: **Commonly FSW tool pin geometries [21]**

a) Cylindrical threaded, b) Three flat threaded c) Triangular; d) Trivex; e) Threaded conical f) schematic of a tri flute

1.2.3 Advantages and Disadvantages of FSW

1.2.3.1 Advantages of FSW

The main advantages of FSW over conventional welding methods are :

1. No melting of the work-piece material involved hence tool eliminating workpice material and tool loss.
2. Shrinkage and distortion are lower even in long welds.
3. In FSW, the defects like voids and porosity are less than the conventional welding process due to un-exist of material melting.
4. Low tensile residual and distortion stress in the resultant welded region.
5. Better mechanical properties.

6. Environmentally safe process due to the absence of radiation and toxic fumes.
7. Lower energy consumption, one welding tool can weld 1000 m from aluminium alloys.
8. FSW is operated in all positions with high quality [22-26].

1.2.3.2 Disadvantages of FSW

There are few disadvantages associated with FSW process

1. The work-piece clamping is a very important criterion in the operation.
2. Slow welding speed leads to longer process time.
3. Due to no filler material involved, the thickness of the weld line will reduce during the welding process.
4. At the end of each weld, the tool caused keyhole as shown in figure **(1.6)**.
5. When large down forces used, heavy duty clamping must be used to hold the plates together.
6. Lower flexible than arc and manual processes [22-26].

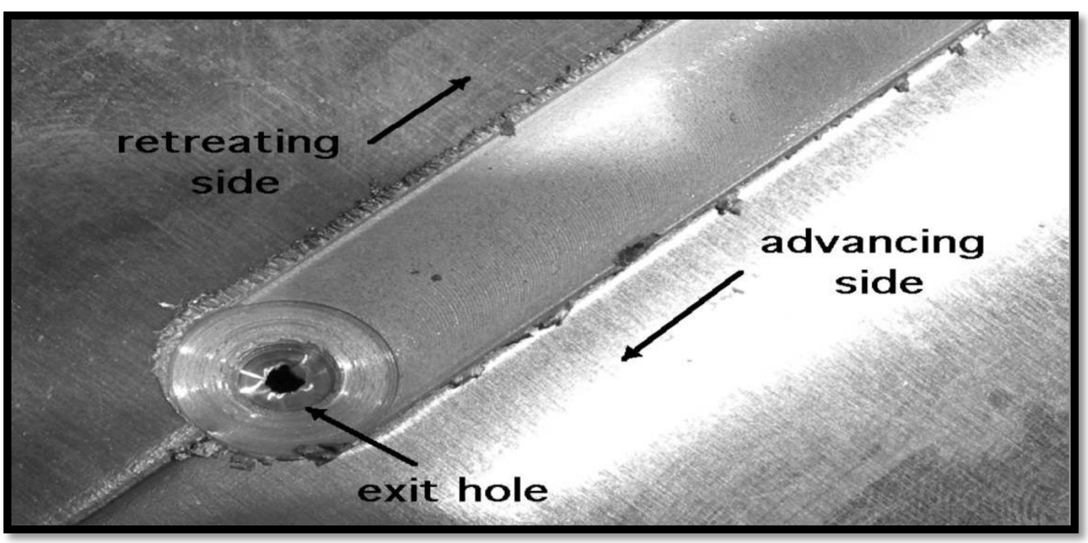

Figure **(1.6):** Exit hole at the end of the welding line in FSW [26].

1.2.3.3 FSW Limitations

1. FS can’t be used in welding of aluminium structures such as a plate with very thick and inaccessible locations and large structures.
2. The main challenges design FSW tool for welding high strength alloys or high melting temperature.
3. The pin length of the tool is not adapted for welding different thicknesses.
4. The machines of FSW are not very flexible although the robotizing of the process improved in last year's [22-26].

1.2.4 Friction Stir Welding of Aluminium Alloys

In aerospace structures getting on high-strength, fracture and fatigue resistance welding alloys are very difficult, such as highly alloyed 2*XXX* and 7*XXX* series. These aluminium alloys considered non-weld able as shown in figure **(1.7)** due to the porosity and poor solidification microstructure in the fusion region, in addition to the high loss of mechanical properties when compared with the base material. These parameters make using conventional welding process to joining these alloys unsuitable. FSW is environment-friendly, an energy-efficient, and multipurpose joining technique that has verified to be one of the most important achievements in the aluminium alloys welding joint field. In addition to bond aluminium alloys, FSW has used to bond steel, Ti alloys, Cu alloys, and Mg alloys [23].

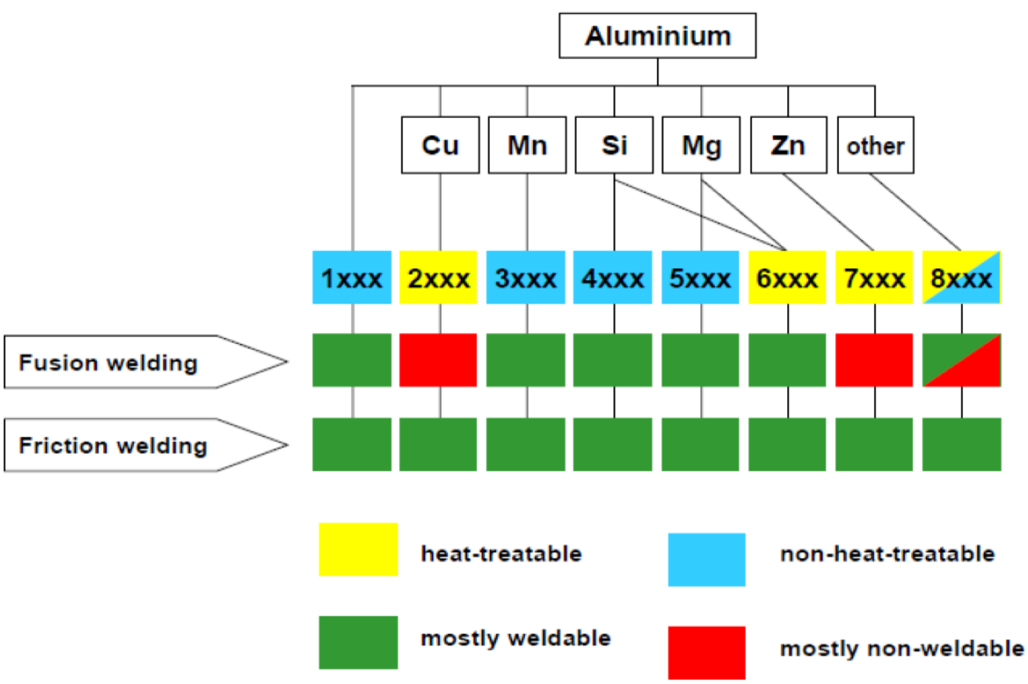

Figure **(1.7):** Weldability of various aluminium alloys [27].

1.2.5 Material that used in this study

The hardening constituent in 6XXX series alloys is magnesium silicide Mg_2Si. Magnesium and silicon are found in small amounts in those alloys, usually less of 1%, and may be further alloyed with equally small amounts of copper, chromium, zinc, and manganese. The change in the structure and mechanical properties in these alloys is complex and strongly depend on the welding parameters [28,29].

Alloy 6061 considers one of the usually utilized alloys in the 6000 Series and it's considered of most versatile of heat treatable alloys. These alloys have good toughness characteristics and medium to high strength alloy. It is the most popular aluminum alloy extrusion. Applications of 6061 range from machinery and equipment applications to transportation components. 6061 alloys have good resistance to seawater and excellent corrosion resistance to atmospheric conditions and it responds well to anodizing and good finishing as well as, welded easily and welded by several commercial methods. 6061 strength in its T6 condition is reduced in the weld zone. The strength properties of 7075 or 2024 are higher than the 6061 [30].

1.2.6 Welding Procedure

Before welding operation the two plates firmly clamped onto the worktable in a manner that prevents the motion and vibration two plates. The procedure of welding operation is divided into five steps [11]:

1. A cylindrical shouldered tool is rotated in specific rotation speed without travel speed as shown in figure (**1.8 A**).
2. In step two the pin slowly plunged into the joint line between two work-pieces, which are butted together as shown in figure(**1.8 B**)

3. The tool (pin) is continuing in plunged into the interface line between two plates until reached specified penetration (3.8) mm and during rotation and plunged tool the frictional heat is generated between the tool and material as shown in Figure (**1.8 C**).
4. Heat generator causes soften without reaching the melting point (70 – 90% from melting point) and permits passing of the tool along the interface line as shown in Figure (**4.10D**). The plasticized material is moved from the advance side of the tool to the retreating side.
5. Stopped the travel speed and begin rising the tool from the welding line. The tool leaves the fixed hole when complete welding is shown in figure (**4.10E**).

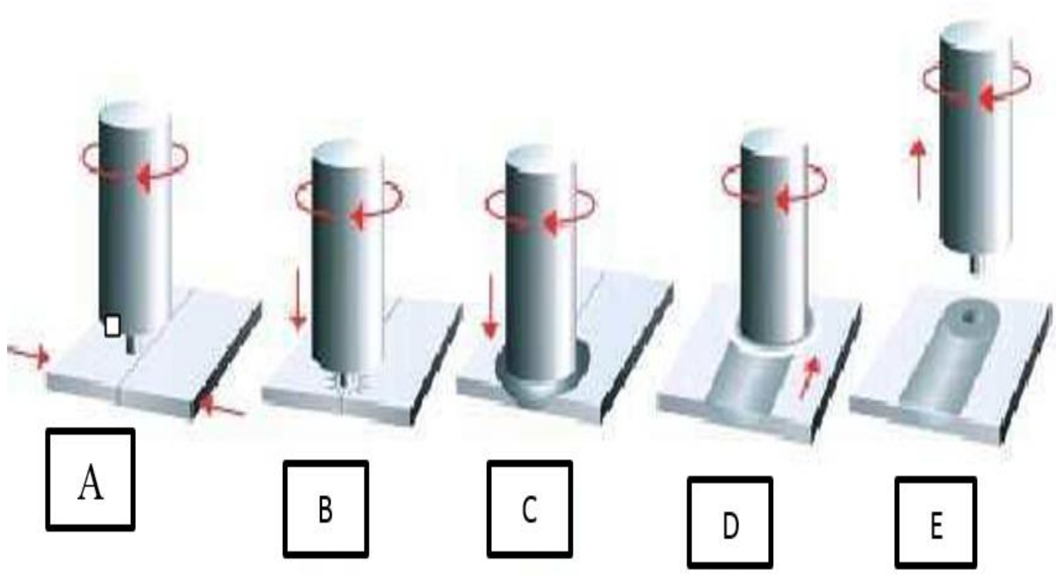

Figure (**1.8**): Steps of welding operations [11].

1.2.7 Applications of FSW

1. FSW has used in Aerospace manufacturing such as fuselage, wings, fins, internal structure, fuel tanks, booster tanks, and rockets.
2. FSW has used in the marine industries and shipbuilding such as Marine structures, boat sections, and sailing boats, helicopter landing platforms, floors and bulkheads and Refrigeration plant.
3. FSW used in high-speed trains made from aluminium, Rolling stock of railways, Trams and Underground carriages, Container bodies, goods Wagons, and Railway tankers.
4. It utilized in Pipe fabrication, Facade panels, aluminium pipelines, window frames, the chemical industry and aluminium reactors for power plants, air conditioners, heat exchangers, and aluminium bridges.
5. It used in the electrical industry, electric motor housings, electrical connectors and others.
6. It used in Cooking equipments, refrigeration panels, gas cylinders, gas tanks and white goods [22].

1.2.8 Defection in FSW

Welding efficiency in FSW is affected to various defects resulted through the welding operation. The defects in friction stir welding involve Flash, Tunnel, Cracks defect Cavity/Groove Void/Wormhole, as shown in the table (1.2).

Table **(1.2)** The defects and its locations [31].

Defection	Location	The cause
Grooves	Lower welding zone Under stir zone	• Higher welding speed • Penetration not suitable • Improper design of welding tool
Cavities	Front part for welding zone	• Higher welding speed • Fixture plates not good • Not completed contact between two plates before welding
Tunnel	Lower welding zone	• Penetration not suitable • Higher welding speed
Flash	On both side of the welding zone	• Unsuitable tool tilt angle

1.2.9 FSW Variables

1. Tool design: length of the pin features on the pin, concave or scroll shoulder.
2. Tool rotations and travel speed rate which effect total heat input.
3. Tile angle of tool tilt, which is typically between 0° to 3°.
4. Joint design: fillet, butt, lap.
5. Cooling rate: passive or active cooling.
6. Initial material temperature: effects on the response of alloy.
7. The thickness of material which has an effect on cooling rate.
8. Alloy composition: weld parameters of one aluminium alloy are not transferable to another.
9. Oxides of surface: the probability of oxides existence in the weld.
10. Test specimen size, location, and orientation: where the specimen is cut from the weld, fundamentally along the longitudinal and thickness vs. transverse orientation.
11. Post weld heat treatment: depend on the heat treatment before welding and composition of the alloy [32].

In this study three varibles (welding speed, rotation speed, and orientation of welding line) were used

1.3 Fatigue

Fatigue is the most important persistent problem in engineering design, ranging from reciprocating components to failure in aircraft and failure of rotating shafts, large civil engineering structures like buildings, bridges and ships. In electronic packages, fatigue problems are commonly found in bond wires, copper plated vies, and solder joints.

When the material subjected to cyclic loading, it would fail at specified stresses that will much lower from the stress that causes failure in static load. The fatigue causes failure in 90% of a mechanical component. Therefore, the study of fatigue failure still very important [33].

1.3.1 Endurance Fatigue Curves

An endurance limit or fatigue limit for specific materials is defined as the level of stress that the material at and below the material does not a fail. These are the properties of titanium and steel in normal environmental conditions. The S-N curve for this type of material is presented in curve A as shown in figure **(1.9).** Numerous non-ferrous metals and alloys, such as magnesium, copper, and aluminium alloys do not display clear endurance limits. These materials have continuously decreasing S-N response such as in curve B in Figure **(1.9)**. In such cases, fatigue strength (endurance limit) for a given number of cycles must be specified. An effective endurance limit for these materials is sometimes defined as the stress that causes failure at 1x 10^8 or 5x10^8 loading cycles [34].

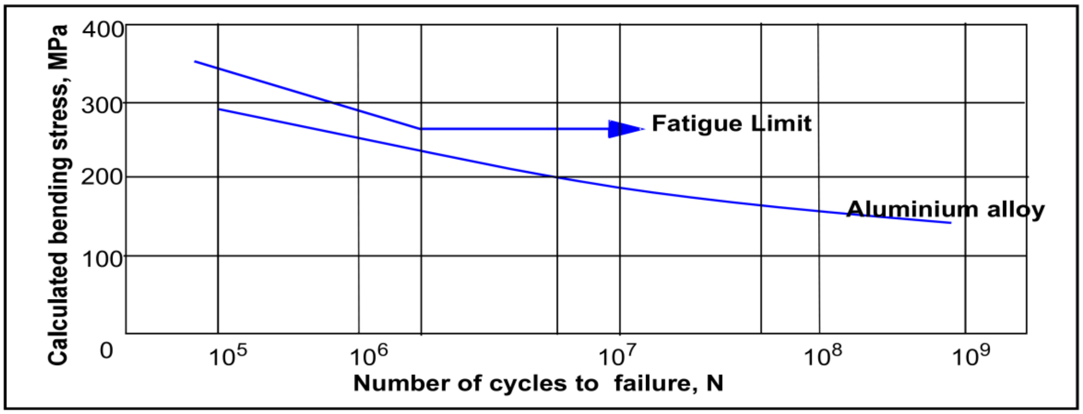

Figure **(1.9):** Endurance fatigue curves [34].

1.3.2 The Relation Between Endurance Limit and Ultimate Tensile strength

The endurance limit is found experimentally fiction of ultimate tensile strength as shown in the table **(1.4)**

Table **(1.4)** The materials and the ultimate strength/ endurance limit [35].

Material	Endurance limit/ultimate strength
Aluminium	0.38
Beryllium copper (heat treated)	0.29
Copper, hard	0.33
Magnesium	0.34
Steel	0.46 - 0.54
Wrought iron	0.63

1.3.3 Fatigue of Friction Stir Welding (FSW)

The incorrect chosen welding parameter has an effect on fatigue failure, as the downward force and pin length. Obviously the weld zone has a change in microstructure which divided into Nugget zone, Thermo-Mechanically Affected Zone (TMAZ), and Heat Affected Zone (HAZ), as shown in figure (1.4). The lower strength area lies between the stirred zone and the base material. Fatigue failure occurs within the welding zone. The initiation of cracks is depending on the testing in as welded or surface machining. While, the propagation of cracks is related to the microstructure of weld zone, as well, the internal defects are never responsible of crack initiation, but they influence on the fatigue strength, providing links between the existing cracks [36].

1.4 Thesis Objectives

The objectives of this thesis are:-

1. Study the tensile strength of AA6061-T6 joint by friction stir welded with a different rotation and welding speed at constant welding tool for three orientation welding line with applied load 45^o, 60^o and 90^o.
2. Using Minitab program to optimization the welding parameters (welding speeds, rotations speeds, and orientation welding line)
3. Use double pass (FSP) to improve the fatigue life for optimum parameters.
4. Numerically analysis fatigue life by using the ANSYS program.
5. Investigate Vickers hardness and residual stress for three cases base material, single pass and double pass (FSP).