CHAPTER - I

INTRODUCTION

1.1 FUSION WELDING AND SOLID STATE WELDING

Welding is known as a versatile metal fabrication process. Welding is a metal joining process that produces a local coalescence of the metals to be joined by heating them to the welding temperature, with or without the application of pressure or with or without the use of a filler metal and application of pressure. All the welding processes can be divided into two major classes

(i) Fusion Welding and
(ii) Solid State Welding

Fusion Welding is a group of welding processes that uses fusion of parent metal to make the weld. Fusion welds ordinarily do not require the application of pressure and may be completed with or without adding of filler material.

Solid State Welding is a group of welding processes which produces coalescence at temperatures essentially below the melting point of the parent materials being joined without the adding of a filler metal. Most of the solid state welding processes require pressure to establish joint. Cold Pressure Welding, Explosion Welding, Friction Welding, Hot Pressure Welding, Diffusion Welding and Ultrasonic Welding are examples of Solid State Welding process.

Welding is used to join materials into parts and parts into structures and assemblies. It is also used to fabricate the machines that make those parts or materials [Ericsson (2012)]. The pipelines used to transport natural gas and oil
from the Bering Sea across Alaska and Canada to the continental United States or across the Ural Mountains from Russia to Western Europe stands evident to the versatility of welding process. The giant 100,000-ton super tankers that ply the oceans moving oil around the world, the numerous off-shore drilling platforms that tap new reserves of oil and natural gas, liquid gas storage tanks, the numerous pressure vessels and pipes in steam and power generation plants, or reaction or storage vessels in the chemical processing industries are a few areas where the impact of welding becomes obvious.

Welding is a process in which materials of the similar basic type or class are joined together through the formation of primary (occasionally secondary) atomic- or molecular-level bonds under the combined action of heat and pressure. Metals are joined in welding through the formation of metallic bonds. The key to all welding is atomic-level inter diffusion between the materials being joined. The diffusion may occur in the liquid, solid, or mixed state. Nothing contributes to joining better than real interchange of atoms, ions, or molecules. The first is to apply pressure and the second is to apply heat.

Heating helps welding to occur in several ways. In the solid state, heating helps by driving off the adsorbed layers of gases or moisture. Then it breaks down the oxide or other tarnish layers through differential thermal expansion between them (or occasionally by thermal decomposition) and finally lowering the yield or flow strength of the parent materials and allowing plastic deformation under pressure to bring more atoms into intimate contact across the interface. Alternatively, heating could help by causing melting of the substrate material to
occur, allowing atoms to restructure by fluid flow and come together to equilibrium spacing once solidification occurs, or by melting a similar filler rod material to afford additional atoms of the same or different but compatible types as the base material.

Pressure aids the process of welding by disrupting the adsorbed layer of gases and moisture by deformation, then fractures the ceramic tarnish layer or brittle oxide to expose clean parent material. Finally, it plastically deforms the asperities to increase the amount of atoms (and the area) in intimate contact.

The relative amount of pressure and heat necessary to produce welds vary from one extreme to the other. Very high heat and no pressure can produce welds by relying on the high rate of diffusion in the solid state at elevated temperatures or in the liquid state produced by melting or fusion. Little or no heat with very high pressure can produce welds by forcing atoms together by plastic deformation, relying on diffusion in the solid state to cause subsequent atomic-level intermixing.

The arc welding process consists of thermally emitted electrons and positive ions from both the welding electrode and the work piece and the intervening atmosphere. These positive ions and electrons are accelerated by the potential field (i.e., voltage) between the source (i.e., one electrode) and the work piece (i.e., the oppositely charged electrode). They produce heat when they convert their kinetic energy by collision with the oppositely charged element. Arc welding includes a large and diverse group of process embodiments or processes. The arc in arc welding is created between an electrode and a work piece at different polarities.
The electrode can be projected to be permanent, serving solely as a source of energy from electrons and positive ions, or consumed, in which case it serves as both a source of energy for welding and filler to assist in making the weld. If the electrode is projected to be permanent, then the process is called "non consumable electrode arc welding process". If the electrode is projected to be consumed, then the process is called "consumable electrode arc welding process". Non consumable electrodes are usually made from tungsten or carbon (in the form of graphite) because of their very high melting temperatures.

1.2 THERMAL ASPECTS OF WELDING

All fusion welding, need heat to allow joints to be produced through the structure of atomic-level bonding. Non-fusion welding processes use friction to produce heat in order to facilitate weld formation or generate heat in the process of forming a weld. The major differences among these processes from the standpoint of heat and its effects are as follows: (a) The peak temperatures reached is a fraction of the parent material's melting point (i.e., the homologous temperature), which is highest for fusion welding; (b) The rate of heating is generally highest for fusion welding; (c) The time at peak temperature tends to be shortest for fusion welding and (d) the rate of cooling once the heating source is removed also tends to be highest for fusion welding.

It is important that for fusion welding processes, not all of the energy available in the source reach the work piece to cause desired heating and melting to produce a weld. Losses occur between the source and the work piece.
As a result, lower temperature sources are less prone to certain types of losses (e.g., radiation of light and heat). The flow of heat or distribution in a welded assembly is governed primarily by the time-dependence of heat, which is identified by the generalized equation of heat flow (dealt later in the modelling chapter). In considering the effects of heat on solidification and melting in the region of melting and on transformations in the surrounding the Heat Affected Zone (HAZ), it is important to consider how the heat is distributed. Heat distribution directly influences the efficiency of melting, the extent and nature of peripheral heating, and the rate of subsequent cooling. The extent of melting, in turn, directly affects the weld size and shape, the homogeneity through convection, the degree of weld shrinkage and weld distortion.

The extent of peripheral heating, in turn, affects the following: (a) development of thermally induced stresses acting on the solidifying zone; (b) The rate of cooling in the solidifying zone; (c) The level of heating in the heat affected zone (which can cause degradation of properties); (d) The rate of cooling in the HAZ (which determines the final structure and properties in this zone) and (e) the degree and nature of distortion and/or residual stresses in the newly joined assembly.

Theoretically it's imperative to understand what happens at a point on the weld as a function of time, from just before the heat source acts on the point to after the heat source is removed from the point. Key aspects to note are:

(a) The temperature starts out at the ambient temperature of the environment prior to the arrival of a moving heat source
(b) The temperature rises very rapidly once the heat source acts on the point.
(c) The temperature reaches a maximum or "peak" determined by the balance between the energy being input and all lost.
(d) The temperature remains at a maximum only as long as the source remains on that spot (which, for a moving source, is only an instant).
(e) The temperature cools back to the ambient level at a rate dependent on the thermal mass and thermal-physical properties of the material and any imposed cooling.

For the GTAW process, the peak temperature can be much higher than the liquidus temperature of the base material being welded. This is typically several hundred degrees Kelvin higher due to the short "dwell time" once melting is achieved. Superheat is needed to ensure that melting is complete. Cooling of the newly formed joint and surrounding HAZ is normally quite rapid (i.e., several hundred degrees Kelvin per second), near the solidification temperature.

1.3 ALUMINIUM AND ITS ALLOYS
1.3.1 Characteristics of Aluminium Alloys

The unique arrangement of properties provided by aluminium and its alloys make aluminium one of the economical, most versatile and attractive metallic material for a broad range of uses from soft, highly ductile wrapping foil to the most challenging engineering application.
Aluminium has a density of 2.7 g/cm$^3$, about one third as much as steel (7.83 g/cm$^3$). Aluminium resists the kind of progressive oxidation that causes steel to rust away. Aluminium can resist corrosion by salt water and other environmental factors, and by a wide range of other physical and chemical agents. Aluminium surface can be highly reflective and hence, electromagnetic waves, radiant heat, visible light, and radiant energy are efficiently reflected by it. Aluminium typically displays excellent thermal and electrical conductivity and is about 50% to 60% that of copper. Aluminium is non-ferromagnetic; a property of importance in the electrical and electronics industry. It is non-pyrophoric, which is important in applications involving handling or exposure of inflammable or explosive materials.

Aluminium is non-toxic and is routinely used in containers for beverages and food. One of the most important characteristics of aluminium is its workability and machinability. It can be cast by any known method, rolled to any desired thickness, forged, drawn, spun, hammereded, stamped, and extruded to almost any conceivable shape. Due to the exciting range of properties of aluminium and aluminium alloys, this group of metals is extensively used for wide range of industrial applications. Aluminium and its alloys can be ranked next to steel, in terms of industrial applications.

1.3.2 Classification of Aluminium Alloys

There are international standards based on which aluminium alloys are designated. These alloys are distinguished by a four-digit number, which is followed by a temper designation code. The first digit corresponds to the principal alloying constituent. The second digit corresponds to variations of the initial alloy.
The third and fourth digits correspond to individual alloy variations. Finally the temper designation code corresponds to different strengthening techniques.

1xxx—Pure Al (99.00 % or greater)
2xxx—Al-Cu Alloys
3xxx—Al-Mn Alloys
4xxx—Al-Si Alloys
5xxx—Al-Mg Alloys
6xxx—Al-Mg-Si Alloys
7xxx—Al-Zn Alloys
8xxx—Al + Other Elements
9xxx—Unused Series

Temper Designation System

   F – as fabricated
   O - Annealed
   H – strain-hardened
   W - Solution heat-treated
   T - Thermally treated to produce stable tempers other than F, O, or H

Subdivisions of T Temper thermally treated:

   The aluminium alloys are classified into two categories: non-heat treatable and heat treatable.
Heat-treatable aluminium alloys

The initial strength of aluminium alloy in this group depends upon the alloy composition, just as the non heat–treatable alloys. Heat treatable aluminium–copper alloys conforming to Al 2024-T6 are of moderate strength and possess excellent welding characteristics over the high strength aluminium alloys. Hence, alloys of this class are extensively employed in marine frames, storage tanks, pipelines, and aircraft applications.

Non-heat treatable aluminium alloys

The initial strength of the non-heat treatable aluminium alloys depends mainly upon the hardening effect and effect of alloying element such as silicon, manganese, iron, and magnesium. These elements increase the strength either by solid solution strengthening or in dispersed phase. The non-heat treatable alloys are mainly found in the 1xxx, 3xxx, 4xxx and 5xxx alloy series depending upon the alloying elements. The strength of all the non-heat treatable alloys may be improved by strain hardening.

1.3.3 Applications of AA 5059 Aluminium Alloy

In this research work, the non-heat treatable alloy AA 5059 H-136 is taken for investigation. This alloy is a magnesium (Mg) based non heat treatable alloy that is strengthened by mechanical strain hardening and is produced at Koblenz, Germany, by Aleris International, Inc.[T. Anderson et al (2003)]. The strain hardening process results in the 5000 series alloy receiving the “H” designation rather than the “T” designation that is typical for heat treatable alloys. Marine grade tempers of 5059, such as H116 and H321, have been commercially available.
for quite some time on yachts, ferries, and catamarans. The H136 designation indicates that during the production process, the plate was only stretched and not cold rolled. This resulted in a lower cost, more ductile version that may provide some benefit as structural material. Nowadays, aluminium alloys are used in many applications in which the combination of high strength and low weight is attractive. Shipbuilding is one area in which the low weight can be of significant value. The AA 5059 is the most frequently used aluminium alloy in shipbuilding industries as a hull material due to its high corrosion resistance. These attributes allow ships to go faster, travel farther, and carry larger payloads given the same amount of fuel load. Also AA 5059, Alustar aluminium alloy is used in military to make a milled vehicle door, due to its excellent ballistic and mine blast deflection characteristics. Due to its lower weight compared to steel plate, this alloy is used as a component element in products such as brackets, braces and armaments. The main alloying element in the 5000 series is magnesium. The higher the Mg content, the greater is the welded strength of the base metal. Al -Mg alloys of the 5000 series are strain hard enabled, and have moderately high strength and very high toughness even at cryogenic temperatures to near absolute zero. They are readily welded by a variety of techniques. As a result, 5000 series of aluminium alloys find wide application in building and construction, highway structures, including bridges, storage tanks and pressure vessels, cryogenic tanks and systems for temperature as low as -270°C and marine applications.
1.4 CHALLENGES IN WELDING OF ALUMINIUM ALLOYS

Aluminium alloys are lightweight, have relatively high strength, retain good ductility at subzero temperatures, highly resistant to corrosion, and are non-toxic. They have a melting range between 482\(^\circ\)C and 660\(^\circ\)C, depending upon the alloy. It is impossible in practice to stop the tenacious oxide film formed due to oxidation at exposed surfaces. Unlike iron, aluminium has only one allotropic form so there are no phase transformations which can be exploited to control its microstructure. The heat generated due to welding can severely hinder the process of deformation and precipitation-hardening of alloys. So, in order to avoid these difficulties, a new technique called friction stir welding was developed. It can weld all aluminium alloys, including those that cannot normally be joined by conventional fusion welding techniques such as aluminium-lithium alloys. Dissimilar aluminium alloys can also be joined, for example, 5000 to 6000 series or even 2000 to 7000 series.

1.5 WELDING OF ALUMINIUM ALLOYS

There are many different methods available for joining aluminium and its alloys. To deploy an appropriate method amongst them, the various factors to be considered are the geometry, strength of the joint and the environmental conditions such as moisture, temperature, inert atmosphere and corrosion. The dominant method for aluminium fabrication is welding. Most alloys of aluminium are easily weldable [Mishra et al.,(2003)]. Thermal conductivity of aluminium is quite high; therefore heat is easily conducted away from the welding area. It is essential that the heat source is powerful enough to rapidly reach aluminium's melting point of 565/650\(^\circ\)C. Coefficient of thermal expansion of aluminium is also high as
compared to steel, so it is prone to distortion and stress inducement if the proper welding procedure is not followed.

Gas Tungsten Arc welding (GTAW) and Gas Metal Arc welding (GMAW) processes are commonly used. Though there are a few problems like porosity, lack of fusion due to oxide layer, incomplete penetration, cracks, inclusion and undercut associated with these welding processes, the other methods like Resistance Welding, Friction Welding and Laser Welding can be employed. Welding results in many physical and chemical changes such as oxide formation, dissolution of hydrogen in molten aluminium and decolourization upon heating [George et al, (2003)].

Aluminium, due to its strong affinity towards oxygen, forms oxides of aluminium, which is common during fusion welding processes. Since, the oxidation of aluminium elevates the melting point of the metal and its alloys, complete fusion is possible when fusion welding process is used. Aluminium oxide is an electrical insulator and if it is thick enough, it is capable of preserving the arc which starts the welding process. So it demands the use of inert gas welding and use of fluxes is necessary while using the process of fusion welding.

Liquid aluminium in its liquid state has a tendency to absorb hydrogen due to its solubility. This paves way for porosity as the hydrogen remain entrapped, when the metal solidifies. Thus the elimination of sources of hydrogen becomes imminent and the metal should be shielded properly from hydrogen. Elaborate pre treatment on the metal and the machine should take care to check the sources of hydrogen.
Another problem faced when welding aluminium is hot cracking that occurs due to high thermal expansion of aluminium. The heat treatable aluminium alloy has many alloying elements. Hence, weld crack sensitivity is of concern.

Another problem posed during fusion welding of aluminium is weldability due to the copper and magnesium content of certain alloys of aluminium making them susceptible to cracking (2000 series, 5000 series, 6000 series and 7000 series).

1.5.1 Gas Tungsten Arc Welding

Gas Tungsten Arc Welding (GTAW) is one of the widely used conventional fusion welding processes for joining aluminium alloys especially thin gauge plates. Figure 1.1 illustrates a schematic diagram of GTAW system. GTAW uses a permanent, non consumable tungsten electrode to generate an arc to the work piece. This electrode is shielded by an inert gas such as helium or argon to prevent electrode degradation by oxidation and hence it has the older and common names like tungsten inert gas (TIG) welding. The quality of GTA welds are
relatively high than that of any of the arc welding processes. The GTAW process can be operated as shown in Fig. 1.2. Current from a power supply is passed to the tungsten electrode in a torch through a contact tube. The tube is usually water-cooled copper to prevent overheating. The gas-tungsten arc welding process can be performed with or without filler (i.e., autogenously). When no filler is used, joints must be thin and tight-fitting square butts. The GTAW process can be operated in several different current modes, including Direct Current (DC) with the Electrode Negative (EN) or Positive (EP), or Alternating Current (AC).

These different current modes result in distinctly different arc and weld characteristics. When the work piece is connected to the positive terminal of a direct-current power supply, the operating mode is referred to as "Direct Current Straight Polarity" (DCSP) or "Direct Current Electrode Negative" (DC-ve or DCEN). When the work piece is connected to the negative terminal of a direct
power supply, the operating mode is referred to as "Direct Current Reverse Polarity" (DCRP) or "Direct Current Electrode Positive" (DC + or DCEP). In DCSP, electrons are emitted from the tungsten electrode and are accelerated to very high velocities and kinetic energy while travelling through the arc. These high-energy electrons collide with the work piece, give up their kinetic energy, and generate considerable heat in the work. Consequently, DCSP results in deep-penetrating, narrow welds but with higher work piece heat input.

About two-thirds of the heat available from the arc (after losses from various sources) enters the work. High heat input to the work piece may or may not be desirable, depending on factors such as: (a) Required weld penetration (dependent on joint thickness); (b) Required weld width (dependent on joint fit up); (c) Work piece mass (dependent on part size and section thickness); (d) Work piece thermal conductivity (high conductivity needing higher heat input) and (e) susceptibility to heat-induced defects, and concern for distortion or residual stresses (with high heat input being problematic in both regards).

In DCRP, on the other hand, the heating effect of the much higher kinetic energy electrons is on the tungsten electrode rather than on the work piece. Hence, larger, water-cooled electrode holders are required resulting in shallow welds and lower heat input. This operating mode is good for welding thin sections or heat-sensitive metals and alloys. This mode also results in a scrubbing action on the work piece by the large positive ions that strike its surface, removing oxide and cleaning the surface. This mode is preferred for welding metals and alloys that oxidize easily, such as aluminium and magnesium.
There is, however, a third mode, using Alternating Current. This mode tends to give some of the characteristics of both the DC modes during the corresponding half-cycles, but with some bias toward the straight polarity half-cycle. During this half-cycle, the current tends to be higher because of the extra emission of electrons from the smaller, sharper, hotter electrode versus a large, blunter, cooler work piece. In the AC mode, reasonably good penetration is obtained, along with some oxide cleaning action.

The electron emission of tungsten electrodes is occasionally enhanced by adding 1-2% of thorium oxide or cerium oxide to the tungsten. This addition improves the current carrying capacity of the electrode, results in less chance of contamination of the weld by expulsion of tungsten because of localized melting of the electrode and allows easier arc initiation. While both argon and helium are used for shielding with the GTAW process, argon offers better shielding because it is heavier and stays on the work. Arc initiation is also easier because the required ionization potential is lower than that of helium. Thus, GTAW process is good for welding thin sections because of its inherently low heat input. It offers better control of weld filler dilution by the substrate than many other processes (again because of low heat input), and it is a very clean process. Its limitations are its limited penetration capability (typically about 3-4 mm) and slow deposition rate (typically less than 1 kg per hour).

1.5.2 Process parameters of TIG welding

The parameters that affect the quality and outcome of the TIG welding process are given below:
a) Welding Current

Higher current in TIG welding can lead to splatter and work piece being damaged. Again lower current setting in TIG welding leads to sticking of the filler wire. Sometimes larger heat affected area can be found for lower welding current, as high temperatures need to be applied for longer periods of time to deposit the same amount of filling materials. Fixed current mode will vary the voltage in order to maintain a constant arc current.

b) Welding Voltage

Welding voltage can be fixed or adjusted depending on the TIG welding equipment. A high initial voltage allows for easy arc initiation and a greater range of working tip distance. Too high voltage, can lead to large variation in welding quality.

c) Welding speed

Welding speed is an important parameter for TIG welding. If the welding speed is increased, power or heat input per unit length of weld decreases. Therefore less weld reinforcement results and penetration of welding decreases. Welding speed or travel speed primarily controls the bead size and penetration of weld. It is interdependent with current. Excessive high welding speed decreases wetting action, increases tendency of undercut, porosity and uneven bead shapes while slower welding speed reduces porosity.

1.5.3 Friction Stir Welding

Friction Stir Welding (FSW) is a relatively new joining process invented at The Welding Institute (Cambridge, UK) in 1991 [W. M. Thomas et al.,(1991)] and
developed initially for aluminium alloys, which allows metal joining without fusion or filler materials. FSW is used widely employed to weld aluminium and its alloys for critical applications as well. Since FSW is essentially a solid-state, without melting, high quality weld can generally be fabricated with absence of solidification cracking, porosity, oxidation, and other defects typical to traditional fusion welding.

FSW can be used to join many types of similar and dissimilar material combinations provided that tool can be developed to operate compatibly in the hot working temperature range of the work pieces. FSW also has potential for bonding many materials that are difficult or impossible to be joined by more conventional methods, including alloys that are susceptible to solidification cracking, high-strength steels, metal-matrix composites, and other advanced alloys. For many conventionally welded aluminium alloys the fusion zones are typically weaker than the base metal.

However, FSW offers a significant quality advantage that it is possible to make welds where the strength of the fusion zone is identical to that of the base metal alloy. Additionally, because the energy input used for FSW is relatively low (no melting occurs), the heat-affected zone (HAZ) or thermo mechanically affected zone (TMAZ) and residual stresses associated with the welds are relatively small. Lower residual stresses mean that distortion associated with FSW is not a large concern as in conventional welding.
1.5.4 Principle of FSW

The two work pieces to be welded, with square mating (faying) edges are clamped on a rigid backing plate. The clamping prevents any movement of work pieces during welding. The shank, shoulder and pin form a welding tool, and this tool can be rotated to a prescribed speed and may be tilted normal with respect to the work piece. The tool is slowly plunged into the work piece material at the butt line, until the shoulder of the tool forcibly contacts the upper surface of the material and the pin is at a short distance from the back plate. Fig. 1.3 shows the schematic representation of friction stir welding. Either the rotating tool is made to move, along the butt line, to the end by applying an axial force or the work piece is moved to the same effect. The pin is withdrawn on reaching the end which leaves a keyhole as shown in Fig. 1.4.

![Schematic representation of friction stir welding](Mishra et.al (2003))
The pin is forced or plunged into the work piece until the shoulder contacts the surface of the work piece. As the tool descends further, its shoulder surface touches the top surface of the work piece and creates heat.

![Fig.1.4 Friction Stir Welding Process](image)

**1.5.5 Stages of Friction Stir Welding Process**

(a) Rotating tool prior to contact with the plate; (b) tool pin contacts plate creating shear; (c) shoulder of the tool contacts the plate, restricting further penetration while expanding the hot zone; (d) plate moves relative to rotating tool creating a fully re-crystallized, fine grain micro structure

The maximum temperature created by FSW process ranges between 70% and 80% of the melting temperature of the work piece. This reduces welding defects and large distortion commonly associated with fusion welding are minimized or avoided. This heat is conducted to both the tool and the work piece. The amount of heat conducted into the work piece dictates a successful process which is defined by the quality, shape and microstructure of the processed zone, as well as the residual stress and the distortion of the work piece.
The amount of heat conducted to the tool dictates the life of tool and the capability of tool to produce a good processed zone. For instance, insufficient heat from the friction could lead to breakage of the pin of the tool since the material is not soft enough. Therefore, understanding the heat transfer aspects of the friction stir welding is extremely important, not only for the science but also for improving the process.

The process is especially well suited to butt and lap joint in aluminium since it is difficult to weld by arc processes. In addition, the FSW process produces an extremely fine grain structure, giving the stir zone unique deformation characteristics compared with other welding processes, and making it ideally suited for applications where impact damage is a concern.

FSW has been demonstrated in a variety of metals, such as steel, titanium, lead, copper, and aluminium. The process is especially advantageous for joining aluminium and has been exploited commercially around the world in several industries.

1.6 MODELING OF WELDING

Welding is a complex process involving the interaction of thermal, mechanical, electrical and metallurgical phenomena. Since it is a complex process, the analytical models and numerical models are very much useful to completely understand the mechanism of heating and bonding.
1.6.1 Need for Finite Element Method

To predict the behaviour of structure three tools adopted such as analytical, experimental and numerical methods. The analytical method is used for the regular sections of known geometric entities or primitives where the component geometry is expressed mathematically. The solution obtained through analytical method is exact and takes less time. This method cannot be used for irregular sections and the shapes that require very complex mathematical equations. On the other hand, the experimental method is used for finding the unknown parameters of interest. But the experimentation requires testing equipment and a specimen for each behavior. This, in turn requires a high initial investment to procure the equipment and to prepare the specimens. The solution obtained is exact but the time consumed to find the results and during preparation of specimens is more. There are many numerical schemes such as Finite Difference Method, Finite Element Method, Boundary Element and Volume Method, Finite Strip and Volume Method and Boundary Integral Methods etc., are used to estimate the approximate solutions to acceptable tolerance.

1.6.2 The Process of Finite Element Method

The Finite Element Method is used to solve physical problems in engineering analysis and design. The physical problems typically involve an actual structure component subjected to certain loads. The idealization of the physical problem to a mathematical model requires certain assumptions that together lead to differential equations governing the mathematical model. The Finite Element Analysis solves the mathematical model, which describes the
physical problem. The Finite Element Method (FEM) is a numerical procedure; it is necessary to assess the solution accuracy. If the accuracy criteria are not met, the numerical solution has to be repeated with refined solution parameters until a sufficient accuracy is reached.

It is clear that the Finite Element solution will solve selected mathematical model with all the assumptions, which reflects on the predicted response. The approximate selection of mathematical model will influence the accuracy of the solution. The mathematical model is solved and checked for the accuracy then refinement is made if required. Depending upon the level of accuracy, the optimization of section or shape is performed by linking the optimization techniques with Finite Element Method.

1.6.3 Field and Boundary Conditions

The field variables such as displacements, strains and stresses must satisfy the governing conditions, which can be mathematically expressed in the form of differential equations. For structured mechanic problems, the boundary conditions may be kinematic which involves displacements, or static, which involves forces and moments. The specified temperature or heat flow/heat flux or convections may be specified in thermal analysis.

1.6.4 Steps Involved In Finite Element Modeling

The broad steps involved in the finite element method are as follows:

1. Divide the continuum into a finite number of sub regions (or elements) of simple geometry such as line segments, triangles, quadrilaterals. (Square
and rectangular elements are subsets of quadrilateral), tetrahedrons and hexahedrons (cubes) etc.

2. Select key points on the elements to serve as nodes where conditions of equilibrium and compatibility are to be enforced.

3. Assume displacement functions within each element so that the displacements at each generic point depend on the nodal values.

4. Satisfy strain-displacement and stress-strain relationships within a typical element.

5. Determine stiffness and equivalent nodal loads for a typical element using work or energy principles.

6. Develop equilibrium equations for the nodes of the discritized continuum in terms of the element contributions.

7. Solve the equilibrium for the nodal displacements.

8. Calculate support reactions at restrained nodes if displaced.

9. Determine strains and stresses at selected points within the elements.

1.7 ORGANISATION OF THE THESIS

In this research work, the subsequent chapters describe in detail the accomplishment of the objectives based on the material used for the work. The second chapter provides the literature available and earlier works carried out in the area of the GTAW and FSW and the simulation of the process along with the motivation for the present work. The third chapter presents the objectives and the methodology of the present study. The fourth chapter describes the experimental procedures for GTAW and FSW joints of AA 5059 aluminium alloy. The procedure to measure temperature and residual stress are elaborated. Specimen
preparation for the evaluation of the weld characteristics is also described. The
fifth chapter contains the modelling principle adopted for the research work. The
boundary conditions, heat source model and the governing equations that are
incorporated into the FE model are defined. The sixth chapter deals in detail the
optimization of the GTAW process parameters by RSM. The resulting temperature
profile and residual stress for the optimized process parameters are presented.
Consequently characterization of the weldment, based on tensile properties,
fractography, macro and micro structure and micro hardness is dealt in this
chapter. The modeling of GTAW process and its validation with experimental
results are presented in this chapter. The seventh chapter deals in detail the
optimization of the FSW process parameters by RSM. The resulting temperature
profile and residual stress for the optimized process parameters are presented.
Consequently characterization of the weldment, in terms of tensile properties,
fractography, macro and micro structure and micro hardness is dealt in this
chapter. The modeling of FSW process and its validation with experimental results
are presented in this chapter. The eighth chapter deals with the conclusions of the
present research work.