Temperature Distribution during Single Pass Multi-Layer Welding in Additive Manufacturing

Mridul Hedau

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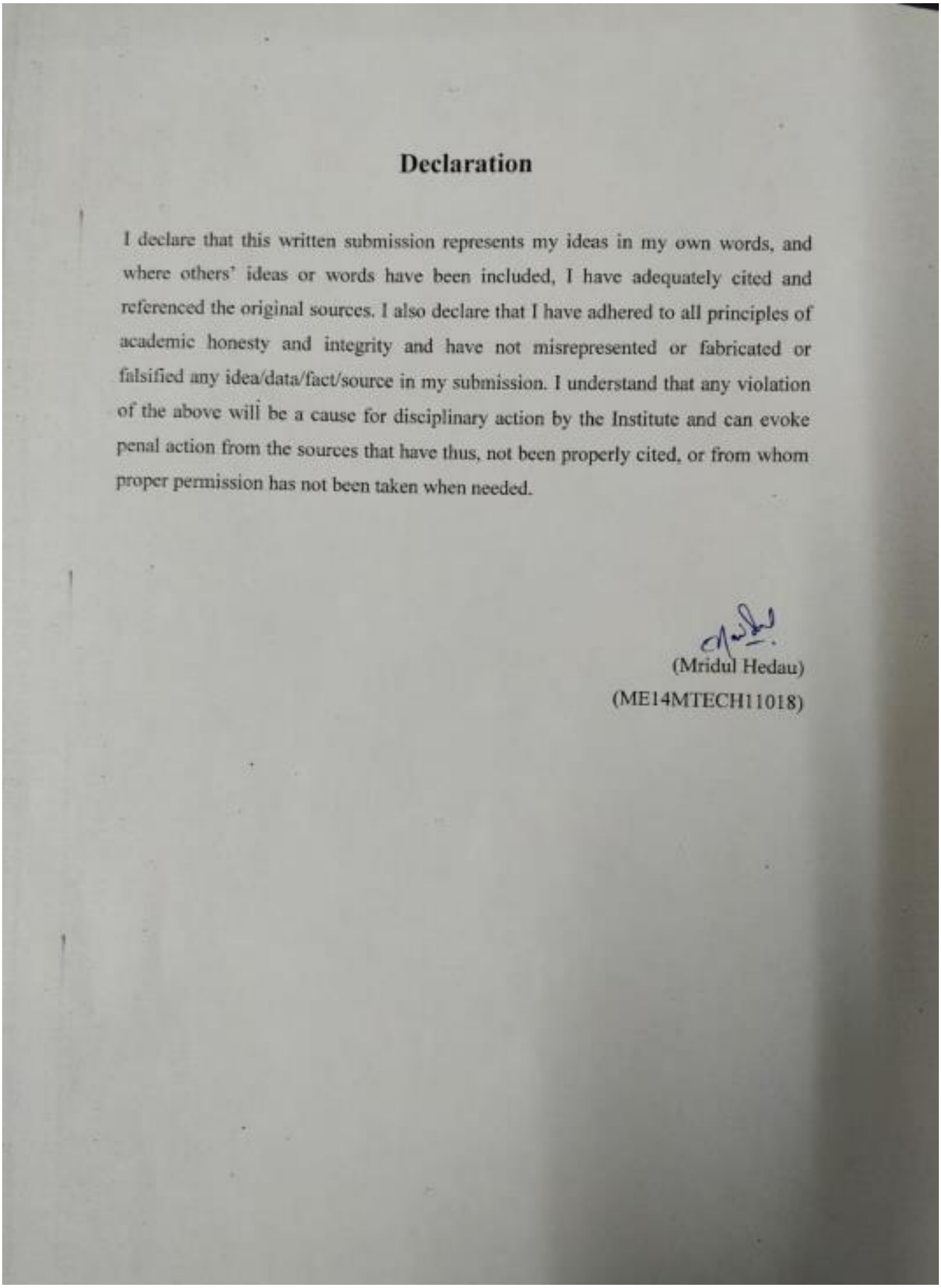

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This thesis entitled 'Temperature Distribution during Single Pass Multi Layer Welding in Additive Manufacturing' by Mridul Hedau is approved for the degree of Master of Technology from IIT Hyderabad.

Dr. S Suryakumar
Examiner

Dr. K Venkata Subbiah 25/6/18
Examiner

Rajesh 25/06/2018

Dr. Rajesh Korla
Examiner

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Above all, I extend my deepest gratitude to **my parents** for their invaluable love, affection, encouragement and support.

Dedicated to

My parents, My strength

Abstract

Single bead welding, is a high-speed welding process that is used for manufacturing of thin walled components. Its application is a vast field of research to assess its ability to manufacture complex products. This is different from the conventional welding of two similar and dissimilar materials in which the focus lies on joining of the two metals. This process is used for the creation of a completely new component by weld bead deposition of material.

Any welding process is a combined process of heating of the material, to create a weld pool, which eventually cools down because of a cooling medium present in the surrounding. This leads to formation of different microstructures in that particular weld bead which determines the strength and characteristics of the weld bead. Thus, a thermal history of the process is required which gives the cooling rate of the weld bead in order to predict the characteristics of the component formed.

This work deals with the feasibility study of joining of two similar and dissimilar metals using numerical modeling and simulation along with its validation with the experimentally performed physical process. The literature gives a brief about the validation done for a finite element model with the experimental results obtained. The model developed in the present study is a basic wall of single weld beads for performing analysis on it.

The future aspects of the project include complex shapes that require tilted axes for manufacturing. The model developed in this study will help in predicting the minimum amount of resources like time and material required for performing a given job. Starting with the joining of same materials, research for simulation of different combination of materials in order to find the weldability percentage between the two joining metals is in progress.

In this study, a thin walled component was obtained through layer-by-layer deposition of mild steel. The initial condition for the deposition of weld bead was the melting point temperature of mild steel. Accordingly, analysis of using different boundary conditions while cooling of the thin walled components was performed. The method of cooling the welded deposit for one model was solely based on the process of convection by air for the walls while maintaining the bottom at a constant low temperature. The second model deals with convection by air on the walls while the bottom has an insulated bottom, i.e. zero heat flux.

The parameters resulted in certain observations and the analyses yielded results, which are discussed below in the document. The study may further extend to analyze the same with inclined complex components as well.

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Chapter 1

Introduction

Manufacturing is a process of producing a component to such a form, which can be used for a specified activity. It is the production of a component from raw material into the finished product. It involves designing as well as specification of the materials to be used for the production of the component. Not all materials can be processed through the same manufacturing process. Thus according to the material, a particular process is selected for its manufacturing. A number of processes are combined together to give a finished product. For performing any job on the material, specified tools are required corresponding to the geometry of the designed product which needs to be manufactured.

Manufacturing of any product requires a streamlined flow of processes required at each step, starting from the concept, designing, tools used for manufacturing and finishing of the produced component. Different types of tools may be required for different levels of designing of the product. A simple flowchart as shown in Fig. 1.1 gives an idea of the required tools for specified designs [1].

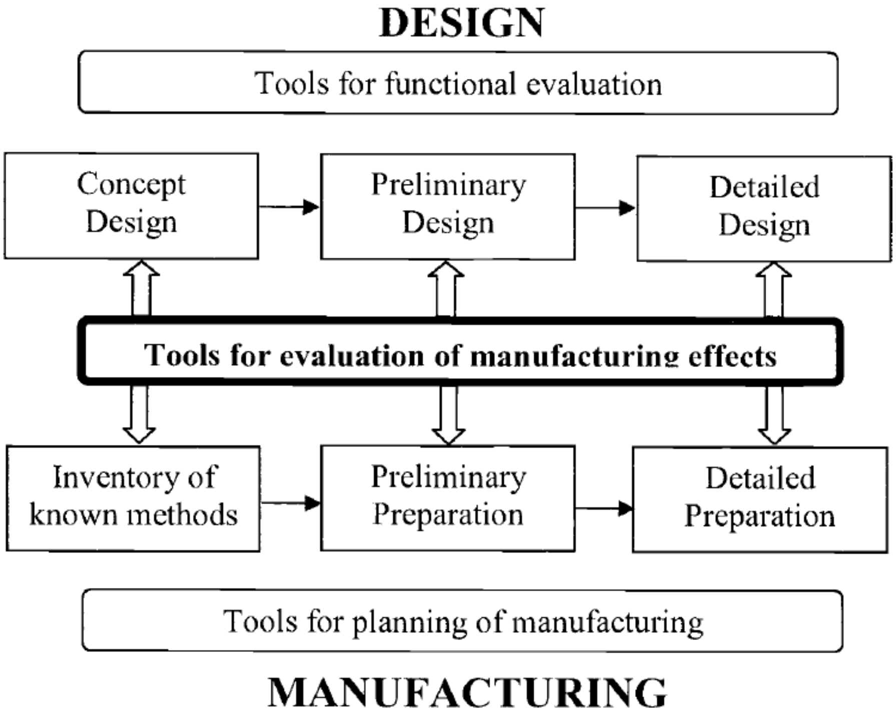

Figure 1.1: Steps involved in manufacturing of a component [1]

Welding is one of the manufacturing processes, which involves joining of two similar or dissimilar metals by the production of heat or pressure between the joining surfaces. There are different types of joining processes like electric arc welding, friction welding, electric resistance welding, etc.

Conventional manufacturing methods involve manufacturing of a product through the process of casting, grinding, forging etc. These methods involve subtractive approach towards the component in which, a lump of material is converted to finished product by performing a number of processes that remove the unwanted material from the lump, giving it a finished shape and thus, the required product is obtained.

Additive manufacturing is an unconventional manufacturing process. It is a process that manufactures a component through layer by layer deposition of the weld on a base material. These layers are developed on a CAD model of the product to be manufactured by a slicing software. These layers facilitate production of a component of any geometry without the use of any specific tool for the manufacturing of the product. This method is suitable for a large variety of materials, polymers and plastics.

This method provides the user with an advantage of negligible points of stresses or weak points since the unsupported part of structure or a separately produced part is directly attached to it. It is formed as a whole product and thus, no compromise on weak areas exists. It has helped new innovative minds to design the products, which could not be manufactured using the conventional manufacturing processes. With the advance research in the field of manufacturing, today additive manufacturing is used for the production of great variety of components.

Chapter 2

Literature Survey

Additive manufacturing is a technology, which facilitates layer-by-layer manufacturing of components without the use of special tools or machines. It is a technology, which facilitates direct fabrication of the components from their CAD models by slicing [2] them into layers. Additive manufacturing gives a better arc stability along with good finishing of the deposited material. Due to stable arc, the distortion is also very less and almost zero spatter created.

A 3D complex product is simplified into a simpler problem by slicing, making the process a combination of several 2D manufacturing problems [3]. This gives the product a staircase effect, which results in better accuracy of the product manufactured. However, when the steps for additive manufacturing used are very small, this may increase the accuracy but consume considerable amount of time.

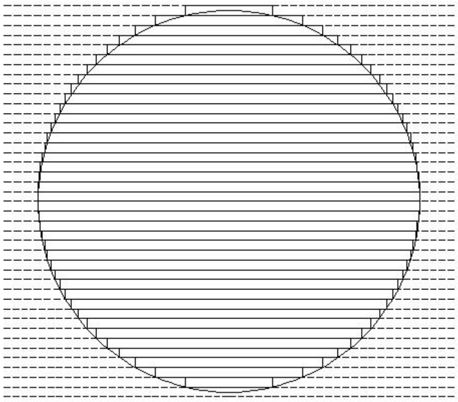

Figure 2.1: Uniform slicing [2]

Complex featured products can be developed using adaptive slicing [3] methods in which the slicing is done according to the required shape of the product. In adaptive slicing, the staircase near the complex surfaces like curves is small as compared to that in the uniform surfaces.

This increases the surface finish of the component produced. To effectively balance the surface finish required and the time consumed in slicing and producing the component, a layer of maximum possible thickness of weld bead is required, which will not hinder the geometry as well will reduce the production time of the component.

The additive manufacturing can be employed for processing a component of same material as well as different materials under a new approach as given by Gibson et al. [4] called as Multiple Materials Additive Manufacturing. This technique makes it possible to improve the microstructural design of the component produced since different materials are used in the areas of high stresses or areas which require a specific type of mechanical property of the component.

This can change the properties of the component containing varying microstructural properties. (as quoted by Murr et al [5]) The only constraint, which is associated with this process, is the time consumed to produce one single component. The process is applied to polymers apart from metals. This process is used for production of small components, which use laser as well as electric arc as a source of energy for welding process.

Additive Manufacturing can be performed with arc welding as well as electron beam or laser beam welding. Arc welding is robust, simple setup with requirement of shielding gas to prevent oxidation of welded material, has high build up rate with a fair accuracy due to thermal distortion and residual stresses. It can be employed for small scale production of components. On the other hand, electron beam welding has a complex setup, with the requirement of vacuum chamber in replacement of the shielding gas as required in arc welding. It has slow build up rate but gives much more accuracy as compared to the arc welding. It is employed for large scale production to make the process economical.

For lower rate of depositions, laser electron beam etc. is used while electric arc welding is used for higher rate of deposition. With higher energy density, electric arc has low energy efficiency as compared to other processes. Researches are putting efforts to increase the efficiency of this process. It is a method which incorporates the physics behind the process keeping in the view the optimization of the process in order to obtain the required product.

When a component with over hanging structure is produced, a base supporting structure is required to support the main over hanging structure. Other manufacturing processes then remove the extra base supporting material. To reduce the wastage of base supporting material, inclined slicing and deposition is being used during large overhang structures. For small overhangs, minimal possible required support structure is provided with this technology. The process can be used for production of components with inclined shape [3,6]. It uses higher axes kinematics which involving tilting different axes to produce a component with or without an overhang structure.

Additive manufacturing, since the days of its inception, has effectively worked towards cost effectiveness of the process, high flexibility to manufacture complex structures and effectively manage resources like time and material not only for large scale production but also for producing single prototypes against the conventional method of manufacturing. For manufacturing of components with costly metals [7,8], it has proved to be a boon.

It is one of the efficient manufacturing methods for newly designed components, which may require special tools and manufacturing facilities and considerable amount of time to setup the facilities through the conventional manufacturing process. This method has various advantages which includes saving of material cost, no process planning, complex geometry production, overall cost reduction and no specific tool required for manufacturing of a particular component. It is, thus, used in the production of aerospace components.

Additive Manufacturing, in recent years, is focused at the functional requirement of the product produced for a particular industry. It includes the operation loads capacity of the component, material strength, porosity or residual stresses which are built up during the process of manufacturing a component. A research based on trial and error method is ensured using the CAD models during Additive Manufacturing to obtain these characteristics [9].

The product can be formed based on the different scales of models related to the type of microstructural level properties required. Research based on different types of scales of modeling like micro, macro and meso level are carried out. Additive Manufacturing can be carried out using wire feed as well as powder bed technology. The following Table 1 compares the two different methods.

Table 1: Comparison between wire deposition and powder deposition method

Sr. no	**WIRE DEPOSITION**	**POWDER DEPOSITION**
1	**Great variety, wider selection**	**Less variety, Limited selection**
2	**Less expensive**	**More expensive**
3	**Faster deposition**	**Slow deposition**
4	**No safety hazard**	**Safety is an issue. Eg: Inhaling is harmful, highly flammable**
5	**Low cost of inert gas**	**High cost of inert gas**
6	**No issues with component porosity and mechanical properties**	**Porosity differs. Thus post processing is required to enhance mechanical properties**
7	**Simple shapes with satisfactory accuracy can be manufactured**	**complex shapes with high accuracy can be manufactured**

In the present study of using additive manufacturing for production of components, single pass multi-layer welding process was used and analyzed. Since additive manufacturing does not require any specific tool for manufacturing of the component, it directly uses a welding torch for the deposition of the material according to the sliced geometry.

The present study deals with electric arc welding. The typical set up of the electric arc welding is as shown in Figure 2.2, in which a feed of mild steel wire is taken for the deposition of the weld. A typical electric arc welding majorly constitutes of an electrode of bead material and power supply in order to create an arc over the work piece on which deposition is to be made.

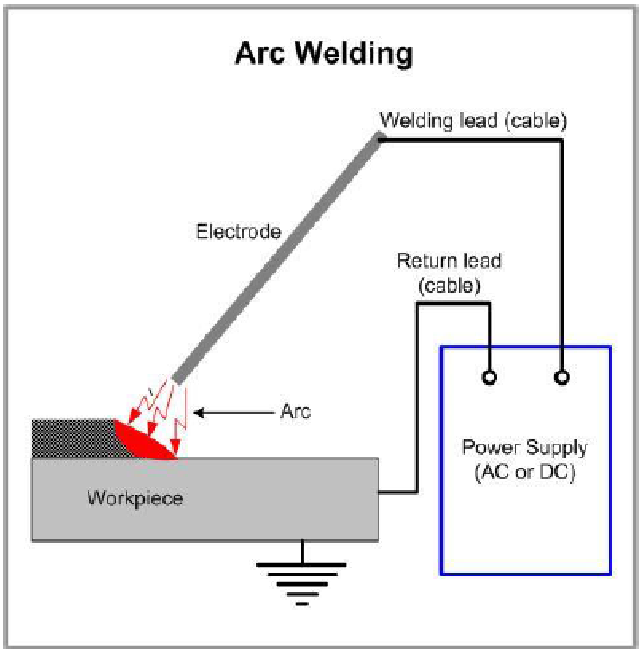

Figure 2.2: Electric arc welding [14]

The parameters involved in welding have a great influence towards the final bead geometry obtained. It includes travel speed and feed rate [7]. But one of the important aspects to be considered when producing a thin walled component using additive manufacturing is the transfer of heat between successive layers.

During electric arc welding, the metal is deposited on a base metal substrate provided by the electrode under the arc produced. A protective covering of the fluxes forms the top layer of the weld due to oxidation of the molten metal with the atmospheric oxygen present. This forms the layer of solidified protective slag coating. The Figure 2.3 shows an overview of the electric arc welding taking place on a substrate. During the welding process, the welded product undergoes residual stresses. These residual stresses have a great impact on the properties of the product produced. This can be treated with the help of thermal modeling.

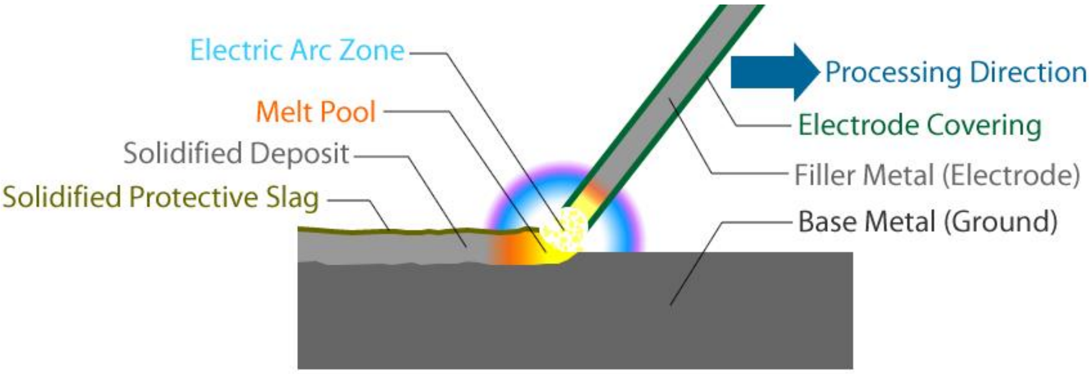

Figure 2.3: Electric arc welding [14]

Gas Metal Arc welding results in high deposition along with low cost for employment of the heat source [10]. It uses high energy input while depositing. This welding leads to thermal distortion and residual stresses. Thus, thermal modeling of the product also plays an important role to determine the surface morphology and the cooling time of the welded product. It can be performed to know the characteristics of the product formed. An extensive literature survey was done under both the effects for manufacturing of the product.

2.1 Thermal modeling of the weld bead

During welding, a weld pool is created of the molten metal as shown in Figure 2.4. The molten metal is surrounded by a Heat Affected Zone (HAZ) which may not be in molten state but has considerable amount of heat flowing through it. It takes a considerable amount of time to cool down these areas.

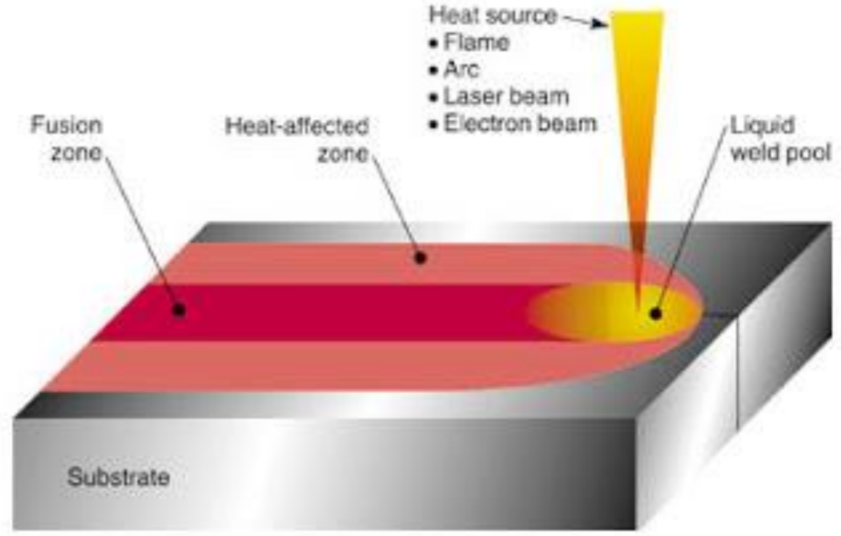

Figure 2.4: Zones during weld pool creation [14]

If the next layer of metal is welded before the required cooling of the weld pool, the geometry of the component may be lost, difference in the bead structure may be observed and the surface topography of the component will not be satisfactory.

For any thermal modeling, an approximation is required with respect to the type of modeling that needs to be done [1]. Figure 2.5 gives a brief about choosing a model for simulation purpose.

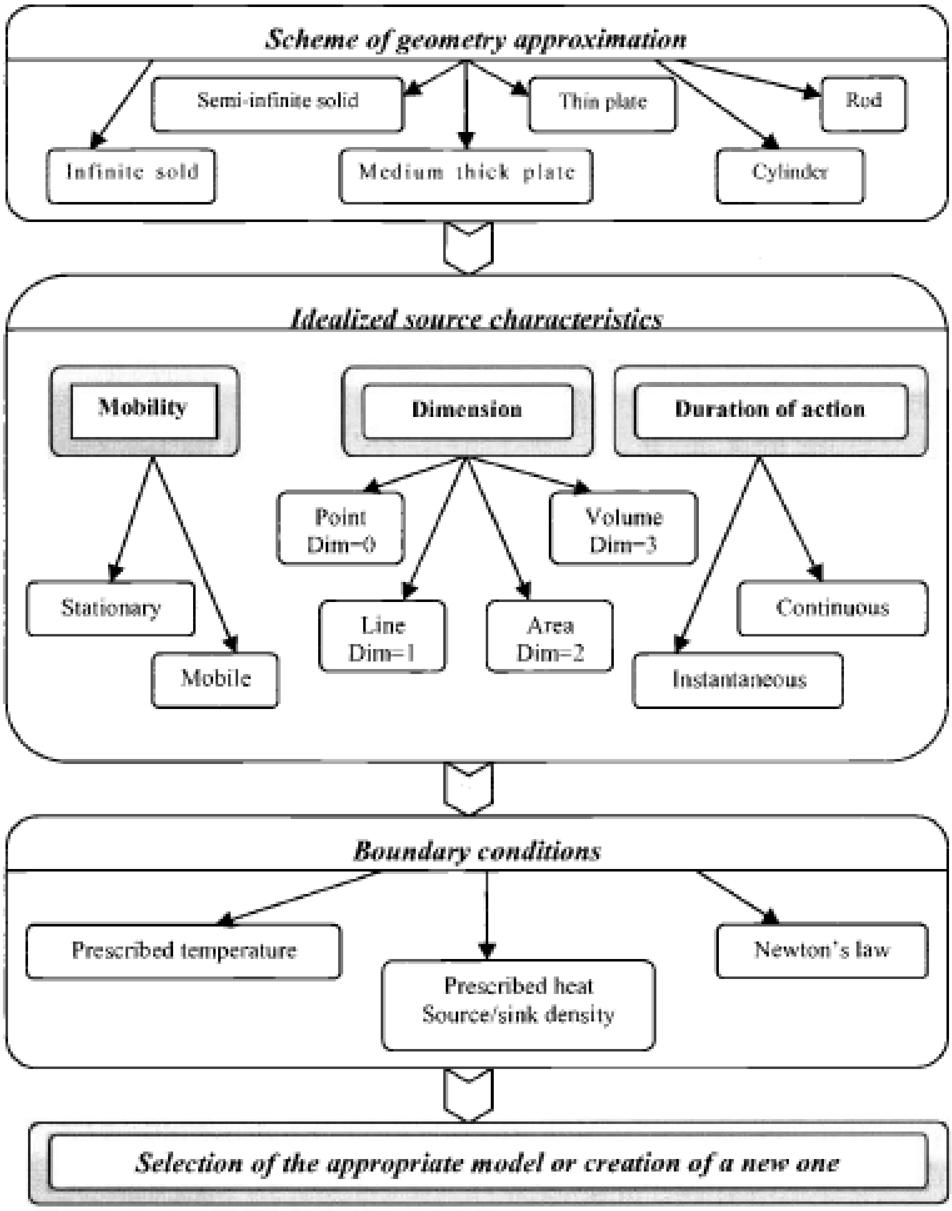

Figure 2.5: Selection of boundary conditions for simulation of a model [1]

A complex distribution of thermal stresses is observed in the layers as they undergo multiple layers of addition of heat, which makes the cooling process complex [9,10], Subtractive manufacturing might have to be used in order to get the component in shape along with unsatisfactory results of the component produced.

On the other side, if more than required timing is given for cooling of the weld bead, the overall time required for the manufacturing of the component will increase, leading to inefficient production of the component. Any deviation from the product geometry will require more processing on it like wastage removal or addition of extra material along with support material for hanging structures etc. This will increase the cost as well as time required to produce the component.

Since the process involves heating of the region due to heat transfer and cooling of the region due to the use of cooling medium, the simultaneous heating and cooling produces stress as well distorts the joints where the welding is taking place.

This gives a clear understanding that control of heat flow i.e. difference in cooling conditions will have a great impact on the welded structure. It will not only give different microstructures, which will result in different strength of the component, but also give different finish to the component. The uneven cooling and distribution of metallurgical properties causes undue residual stress, which affects the mechanical properties of the weld joint if proper care is not taken of.

2.2 Effect of residual stresses on the weld bead

The residual stresses in a component come into existence due to the difference in the cooling and heating rates of the elements of the component [12]. This stresses determine the areas of strength and weakness in a particular component. Vladimir et al [13] brings out the effects of residual stresses produced in thin walled components that affect the mechanical properties like deflection, bending etc. when the component is put under load of various nature. The multiple layer head addition, keeps building up the stress which is reflected in the geometry of the component as shown in Fig 2.6.

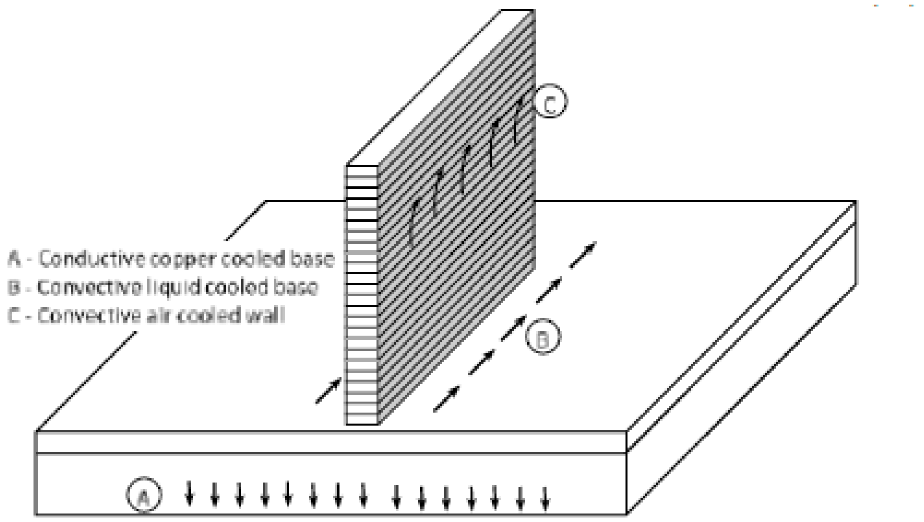

Figure 2.6: Layer addition of welded material along with cooling mediums [11]

During any welding process, a weld pool is created which when solidified gives a unique property to the material. The microstructural properties pertaining to material are a function of the cooling rate of the welded pool. Thus thermal management is required between layer from time to time during production. The study related to the thermal stresses, cooling rate and thermal weld cycle becomes important part of the study to produce component with optimized parameter as well as considerable strength.

Thermal history would help in determining the characteristics of the material. This thermal history can be obtained by a simulation of the process with the help of thermal analysis in software like ANSYS, which can help predict the type of material, which will be obtained once the welding is done and cooled using a certain cooling medium.

The aim of the study is to do a simulation of the single bead welding of components and validate it with the experimental results obtained for the same boundary conditions. The simulation is carried out in ANSYS in order to correlate it with the data that is used in performing the physical process. This will provide an insight with respect to how much time and resources will be consumed in total, which will lead to better management of resources.

The study involves study of two models cooled using different medium of coolants. One uses air by convection for the side walls to cool down along with maintaining the base at a constant low temperature while the other model uses air for side wall convection but maintains zero heat flux at the bottommost layer of the component, i.e. insulated bottom of the material. This document discusses the thermal graphs and the cooling time graphs obtained during the simulation of both these models.

Chapter 3

Finite Element Modeling

Single pass multi-layer welding is a process in which one welding torch is used at a time in order to deposit one layer of weld. Multiple layers are deposited on the base layer in order to produce the required geometry of the component. The weld may be deposited on the top on one another or side by side of the deposited layer, depending upon the geometry of the product to be manufactured. The weld bead may be deposited in opposite directions in order to obtain the uniformity in the distortion being caused by the heat transfer. This reduces the time travel of the weld torch but at the same time the geometry surface finish is lost.

During this study, a single bead multi-layer welding was performed to manufacture a thin walled component and analyze the time required to cool down the product along with the heat flow pattern in the component.

Finite element modeling was used in order to find the thermal distribution and stresses in the component. Any finite element modeling requires a set of boundary conditions applied to the model, based on assumptions, which makes the simulation closer to the realistic environment. A simulation’s accuracy and authenticity is closely related to the type of assumptions made during the simulation.

3.1 Boundary Conditions

The model is assumed to be a thin structure with heat transfer taking place only in y direction in which the weld bead is laid layer by layer in order to manufacture the component. The heat transfer in the x and z axes are assumed to be negligible as compared to that in y axis. Thin walled structure refers to a geometry whose one dimension properties are different from the properties in the other two axes by a large magnitude.

The model is assumed to follow Rosenthal's Simplified Assumptions. They are:

(i) Heat source provides uniform energy input
(ii) The movement of the torch is at a constant speed along the Z axis direction
(iii) Thermal properties like Heat capacity and thermal conductivity are constant
(iv) Heat source is a point source, all energy being deposited at a single point at a time

The model is governed by the following equation:

$$k(\frac{d^2T}{d\xi^2} + \frac{d^2T}{dy^2} + \frac{d^2T}{dz^2}) = -C\rho\frac{dT}{d\xi} + C\rho\frac{dT}{dt}$$

Where,

T is temperature in Kelvin
ξ is fixed distance from origin
k is thermal conductivity
C is specific heat
ρ is density

The assumptions are based on basic principles of welding and metallurgy. These assumptions provide with a near to realistic environment for simulating the process and proceed with the findings.

3.2 Process Parameters

In order to analyze the model, the following properties of mild steel were used, as tabulated in Table 2.

Table 2: Process Parameters

Sr. no	**Parameter**	**Value**
1	**Temperature for the top most layer**	**2000^0C**
2	Thermal conductivity	50 W/mK
3	Specific heat	500 J/kgK
4	Density	7800 kg/m^3
5	Initial temp of weld bead	2000^oC
6	Ambient temperature	30^oC
7	Material	ER70S-6 M

3.3 Simulation

This part of the chapter describes the simulation work carried out for single bead welding of mild steel to produce a thin walled component. The simulation was done in order to validate it with the experimental analysis carried out for the same process. The simulation also provides an insight to the time consumed by different layers to cool down. A pattern of heat flow within the component is also simulated.

The model geometry and process parameters constitute the first part of the document. Modeling and applying of boundary conditions form the base of any simulation. Using Finite Element Analysis, its assumptions and equations governing the process, ANSYS was used to carry out the simulation. Figure 3.1 shows the meshed model.

The model geometry was given with the properties of steel, which constituted basic properties like thermal conductivity, density, isotropic conductivity etc. A fine mesh was generated on the model geometry to create elements over which the boundary conditions are applied. Each element undergoes different thermal characteristics since each element is subjected to stresses that differ in terms of direction and magnitude.

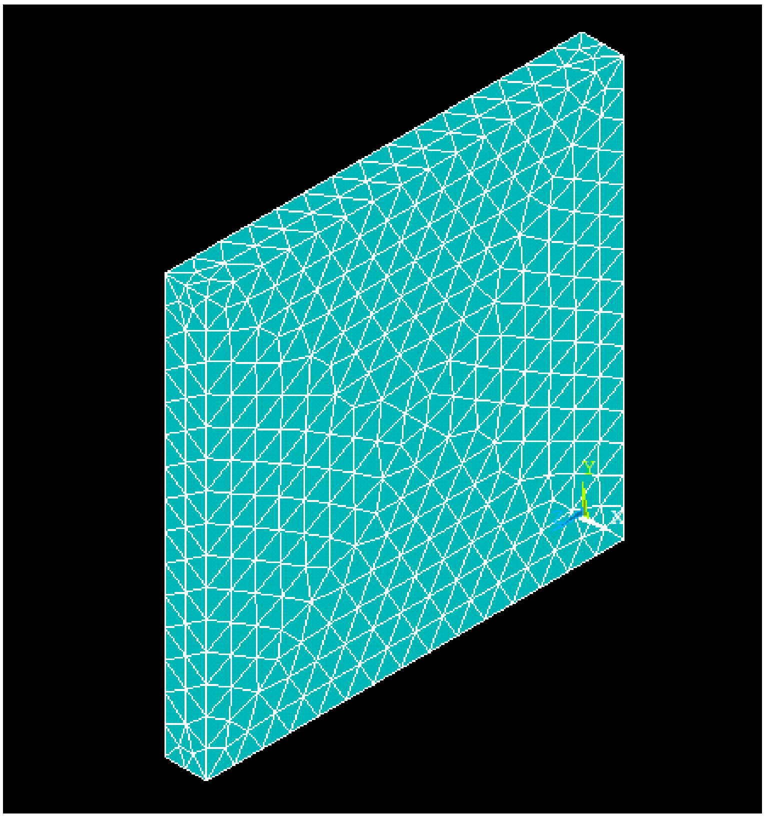

Figure 3.1: Meshed model

The focus of the simulation lies in the heat transfer between the layers and the overall time taken for the material body to cool down. Two types of models were developed and compared based on heat transfer. The first model was assumed to be cooled by convection from all the surfaces, the bottom being maintained at a constant low temperature while the second model is assumed to be insulated at the bottom side, facilitating cooling only through convection by sidewalls by air. The results of the modeled component were analyzed and are as discussed in the report.

Figure 3.2 shows the boundary condition applied on the model. The side walls are applied with convection by air. The bottom layer is applied with a constant uniform temperature of low value for the first model while for the second model a heat flux of zero magnitude, simulating the condition of insulated bottom is applied. The top layer is applied with a high degree melting temperature of steel. A moving source of heat is applied on the elements of the top layers which travel with time along the length of the component, simulating the welding process in the direction of the length of the component.

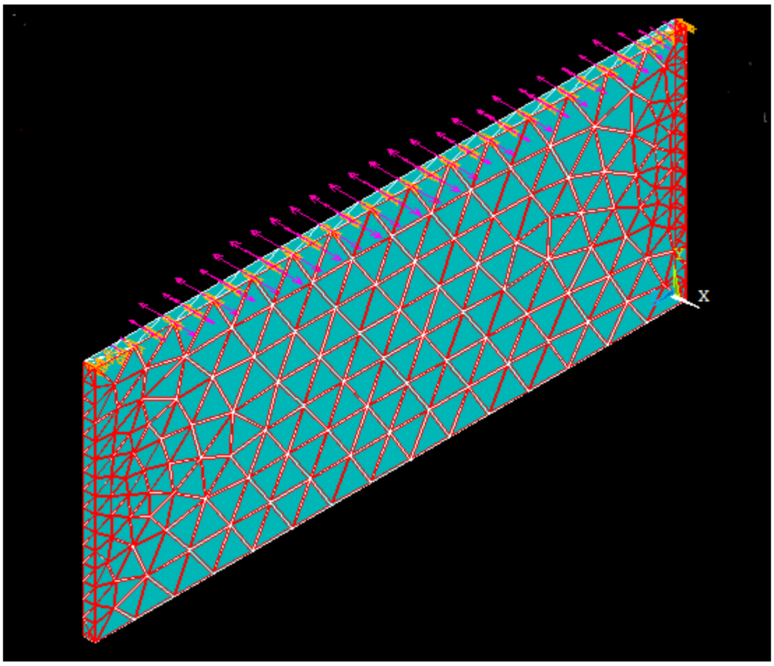

Figure 3.2: Model with the boundary conditions applied on it

3.3.1 Condition 1 (Fixed Base Plate Temperature)

The model deals with the uniform transfer of heat from the sidewalls of the single bead welded component by the process of convection by air. The bottom of the component was maintained at a constant low temperature that facilitates the removal of heat. The model was considered for the heat distribution between the different layers during welding.

The temperature applied to the weld bead on the topmost layer is equivalent to the melting temperature of steel, while the bottom layer is equivalent to ambient temperature, i.e. the bottom layer is maintained at a constant temperature. A normal convection through air, being the medium of heat transfer is considered. A transient analysis of the model was carried out with the above boundary conditions.

The temperature distribution result obtained as shown in Figure 3.3 describes the flow of heat in the component body in the direction of the layer deposited. It was observed that the heat flowing in the direction of the width of the component is negligible as compared to the direction of deposition. Thus, the heat transfer dominates in the direction of deposition of weld bead.

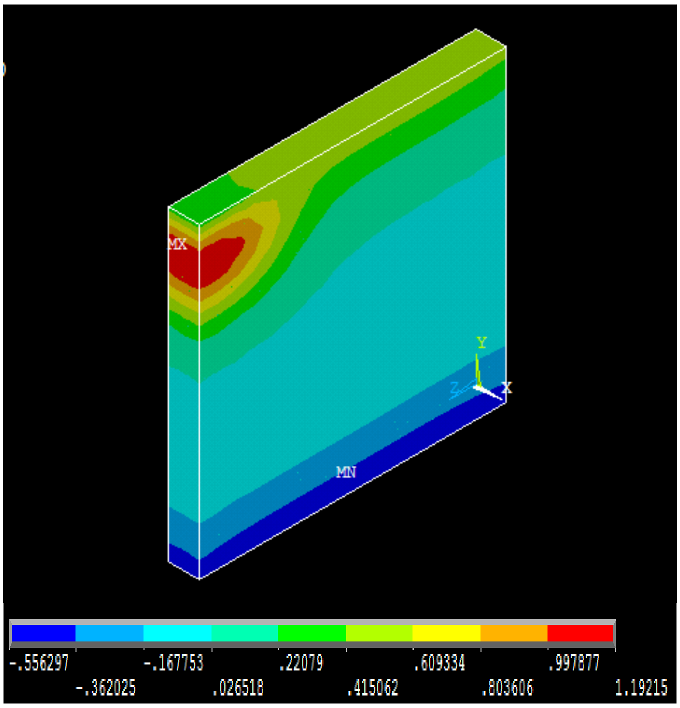

Figure 3.3: Temperature distribution in the direction of layer deposition

A graph as shown in Figure 3.4 gives a distribution between the temperature of the layers of deposition and the time taken to cool down. This yielded the time for cooling down of the model.

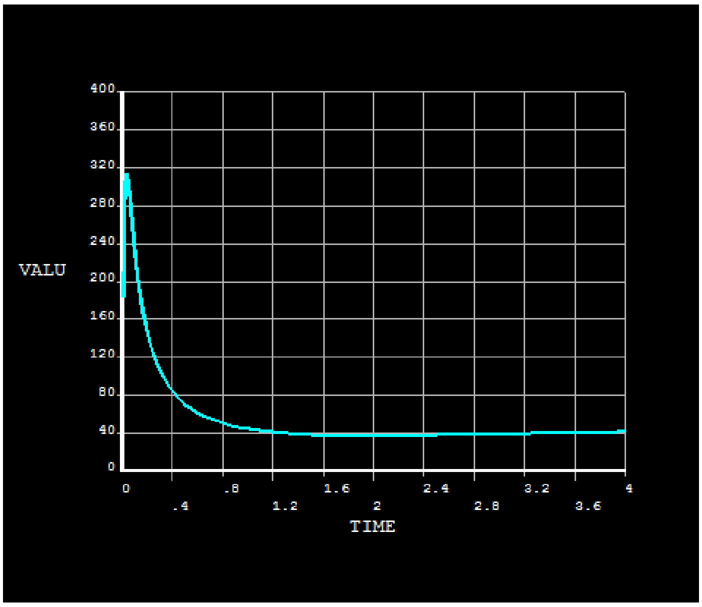

Figure 3.4: Temp(^{0}C) vs Time(hours) plot for the center of the welded deposit under Condition 1

Since the direction of flow of heat is majorly only unidirectional, Figure 3.5 shows the pattern of distribution of heat transfer in the model. It highlights the transfer of heat in y axis along with the transfer in the direction of the weld bead deposition.

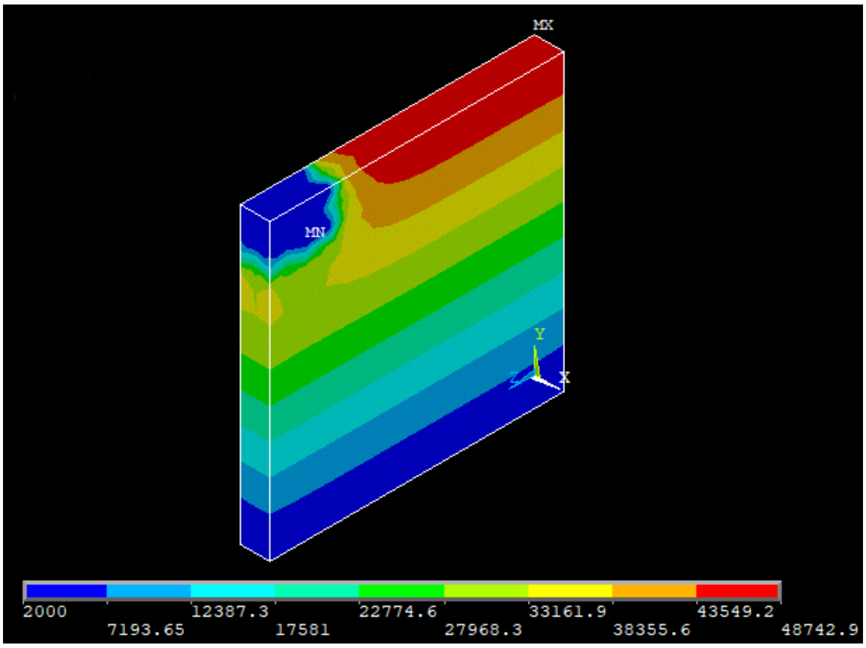

Figure 3.5: Heat transfer in the vertical direction along with the heat source movement in longitudinal direction

3.3.2 Condition 2 (Isolated Base Plate)

This model deals with the uniform transfer of heat from the walls of the single bead welded component by the process of convection by air but has an insulated base plate at the bottom, i.e. the bottom most layer has nil heat transfer (zero heat flux). The topmost layer is given the same temperature of melting steel as that in Model no 1 simulation. The temperature variation of the model is as shown in the Figure 3.6

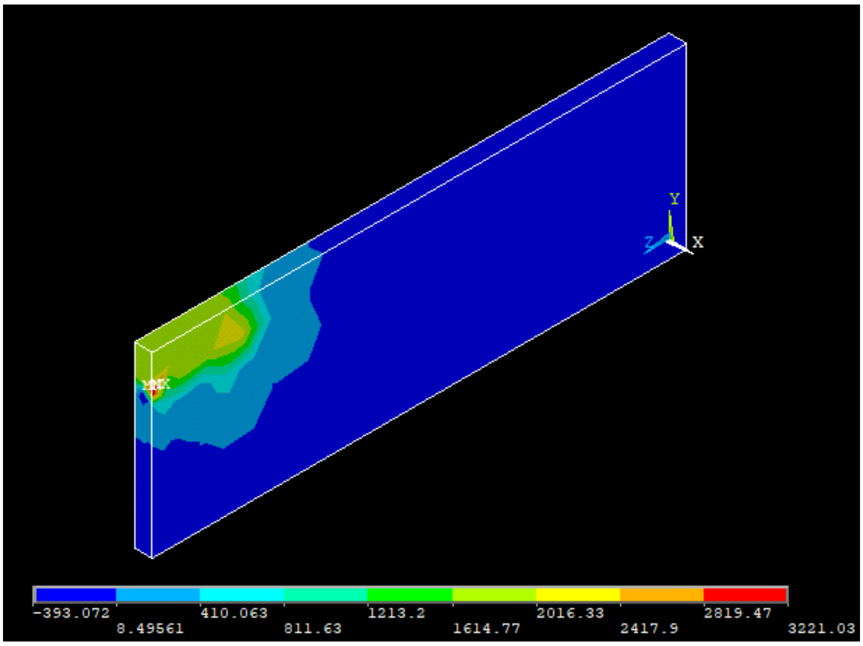

Figure 3.6: Model depicting the flow of heat in the body during the weld deposition process

The body was considered to have different layers of heat addition, with the top layer adding heat to the body and a constant heat flux of zero magnitude was maintained at the bottom most layer. A transient analysis of the model was carried out whose temperature distribution is shown in Figure 3.7.

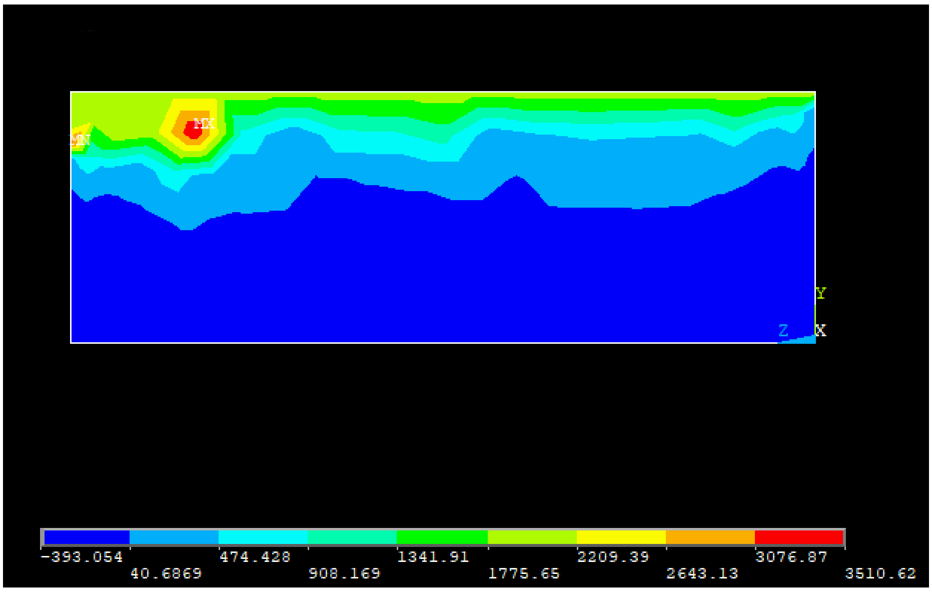

Figure 3.7: The heat source moving in the direction of the weld deposition

The boundary condition applied is same as that in the Model 1, except the bottom most layer. Since the bottommost layer is insulated, the heat is contained in the body, which slows down the process of cooling of the weld. This leads to an overall increase in the temperature of the body.

The graph obtained for the average cooling time of the weld bead over the distance covered by the heat source is as shown in Figure 3.8. It shows a trend of graph in which a certain increase in the temperature of the component is seen due to the effect of insulated bottom, before the component cools down towards reaching an equilibrium with the ambient temperature.

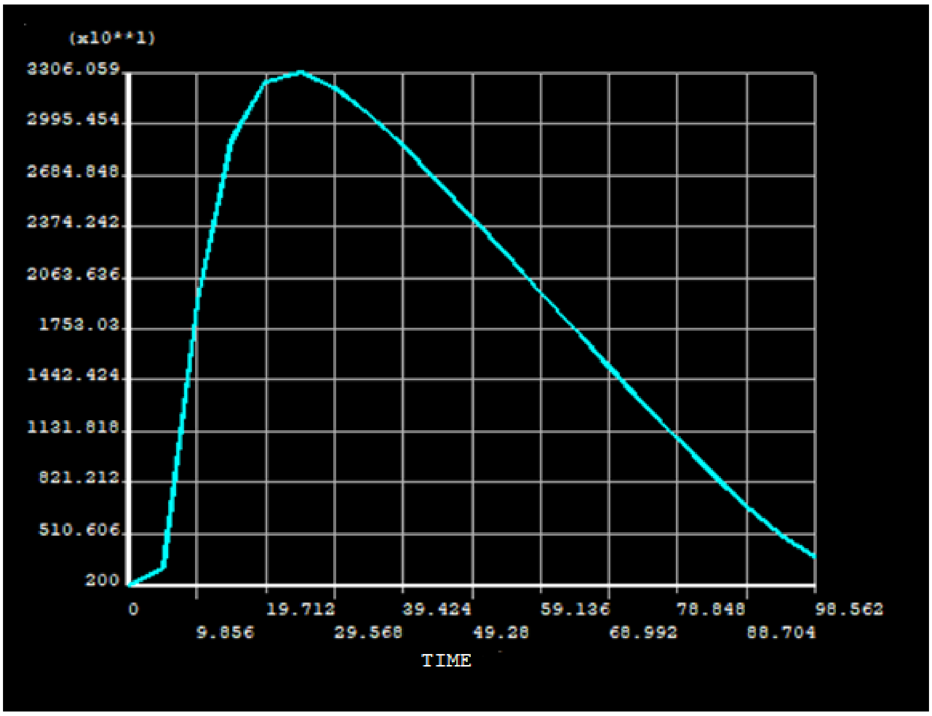

Figure 3.8: Temp(^{0}C) vs Time(s) plot for the deposition under Condition 2

3.4 Results and Discussion

The models were analyzed at different cooling rates with different boundary conditions for both the models. The graphs obtained depicting the cooling time and cooling pattern of the single bead welded component gives a perspective to the type of microstructure being developed in the component as well as the residual stresses that are developing inside it due to the heat addition and removal of heat at the same time.

3.4.1 Condition 1 (Fixed Base Plate Temperature)

A graph for the topmost element provided with the highest temperature on the model, reaching its lowest temperature is as shown in Fig 3.9. This plot shows the temperature fall during cooling of the element through the layers of the component produced. The topmost element is provided with the melting temperature of the stainless steel. It follows the law of thermodynamics to cool down to the room temperature by transfer of heat through conduction and convection.

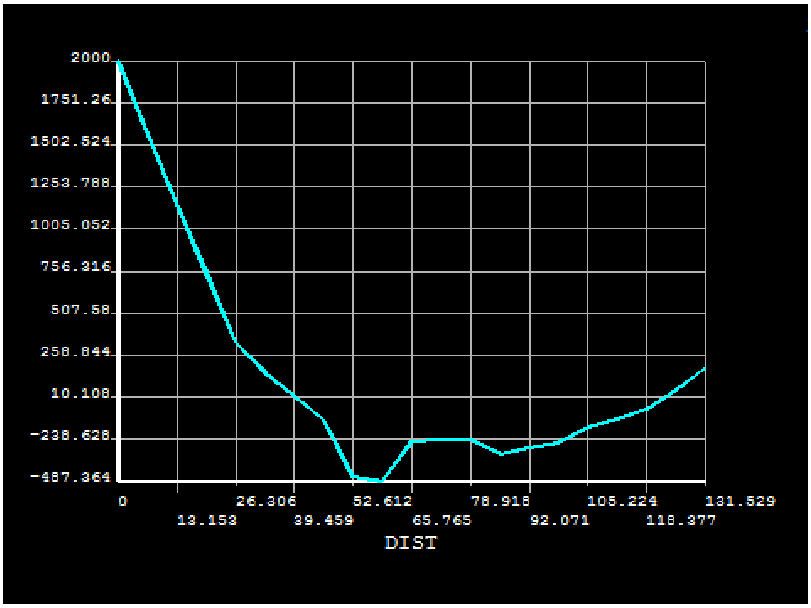

Figure 3.9: Temp(^{0}C) vs weld deposited(mm) plot for topmost element

The graph below in the Fig 3.10 describes the temperature drop of a heated element with respect to the distance travelled by the weld bead. This graph is of the element on the layer immediately below the one on which welding is being done. The heat flow through conduction is experienced from the layer on the top of it as well as the ones, which are below it and have not cooled yet. Since there is only heat conduction from the consecutive layers below the element in addition to the heat transferred by the weld the following graph is obtained for the cooling of the element.

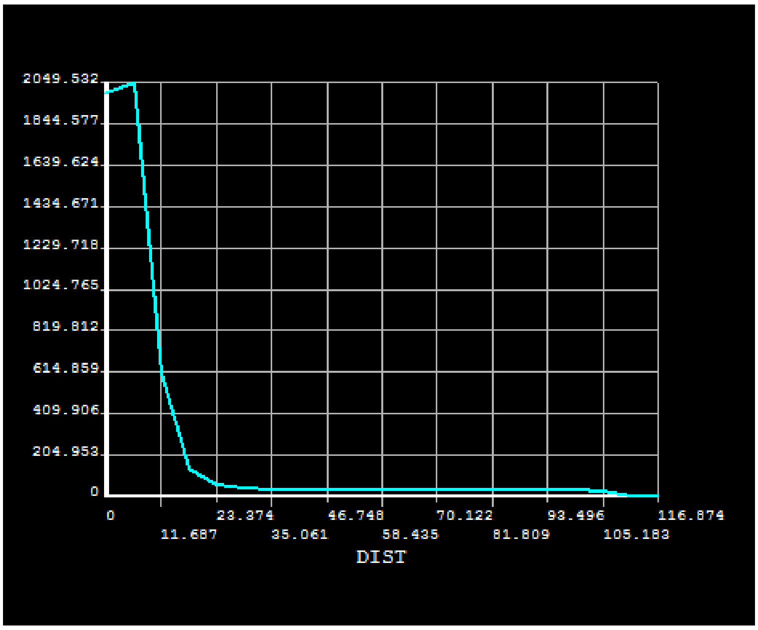

Figure 3.10: Temp(^{0}C) vs weld deposited(mm) plot for element below the top layer

The middle layered element was analyzed. The graph as shown below in Figure 3.11 describes a disrupted temperature graph due to the constant heat addition through the elements surrounding this element from all the sides. The elements transfer heat from the above and below layers to the element being analyzed. Simultaneously, heat is also being taken away from the element through the convection process by air as well conduction to the elements at a lower temperature than the concerned element.

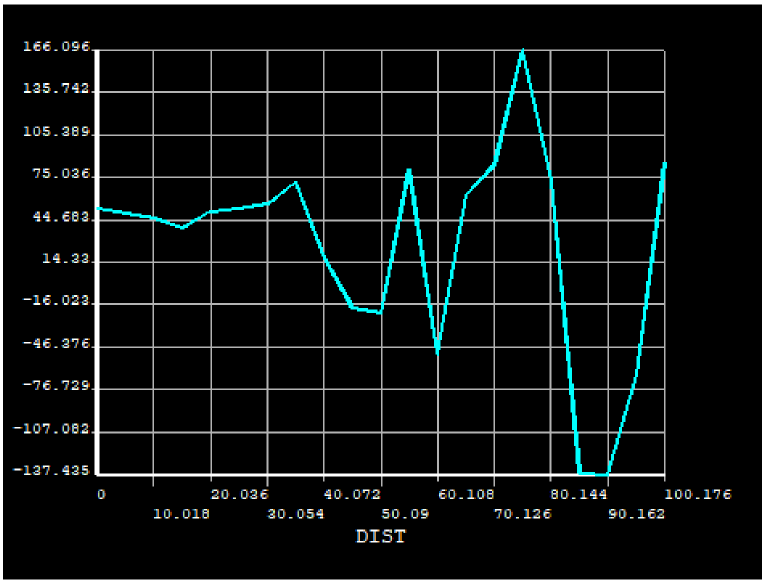

Figure 3.11: Temp(^{0}C) vs weld deposited(mm) plot for middle layered element

A very abrupt change in temperature (as shown in Figure 3.12) was observed in the element, which is in direct contact with the base layer which maintains it at a constant low temperature. This element refers to the lowermost element of the weld beaded component. Even though the heat addition is taking place, the heat flux crossing the element withdrawing heat from the body is much higher than the heat flux added to the element per unit time.

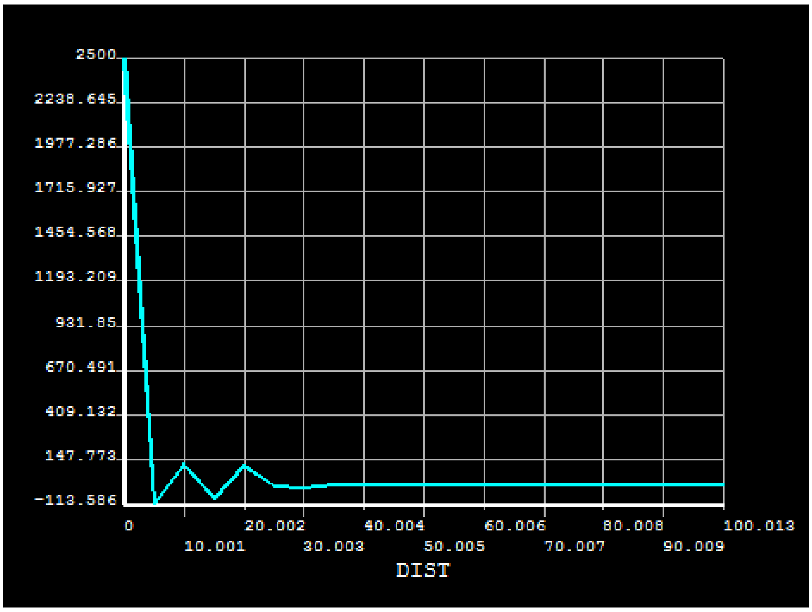

Figure 3.12: Temp(^{0}C) vs weld deposited(mm) plot for the lower most element

3.4.2 Condition 2 (Isolated Base Plate)

The graph below in the Fig 3.13 describes the temperature drop of heated element with respect to the distance travelled by the weld bead. This graph is of the corner most element on the top layer at an input temperature of 2000^{0}Celsius. It encounters a heat inflow from the direction of weld bead deposition due to conduction. The temperature of the element drops due to the cooling taking place through convection, air being the medium of cooling. But due to the insulated base condition of the model, a constant heat addition is seen which reduces the cooling effect taking place at the walls due to convection by air. Thus, a little more gradual drop in temperature is seen as compared to the rapid drop in Model 1 of the same element with different boundary condition.

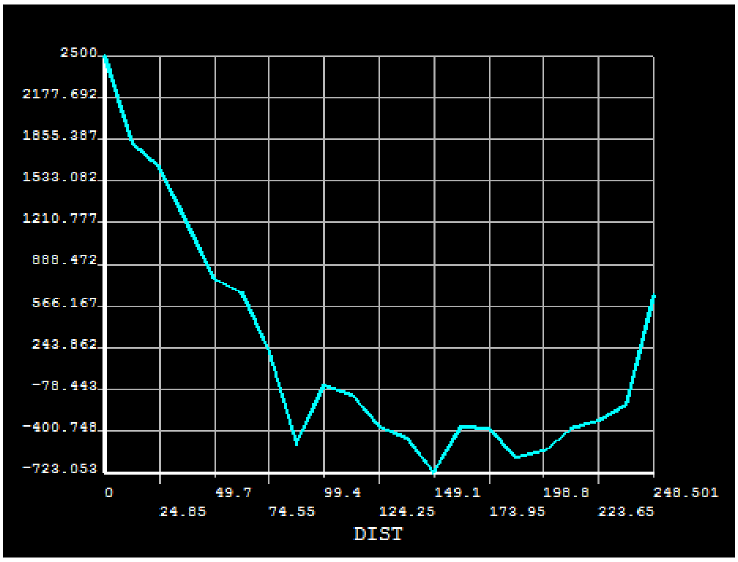

Figure 3.13: Figure 3.12: Temp(^{0}C) vs weld deposited(mm) plot for the top most element

The graph below in the Fig 3.14 describes the temperature drop of a heated element with respect to the distance travelled by the weld bead. This graph is of the element on the layer immediately below the one on which welding is being done. The heat flow through conduction is experienced from the layer on the top of it as well as the ones, which are below it and have not cooled yet. Since there is heat conduction, not only from the consecutive layers below the element, but also from the heat accumulated due to the insulated base condition of the model, a gradual drop in temperature is seen as compared to the rapid drop in condition 1.

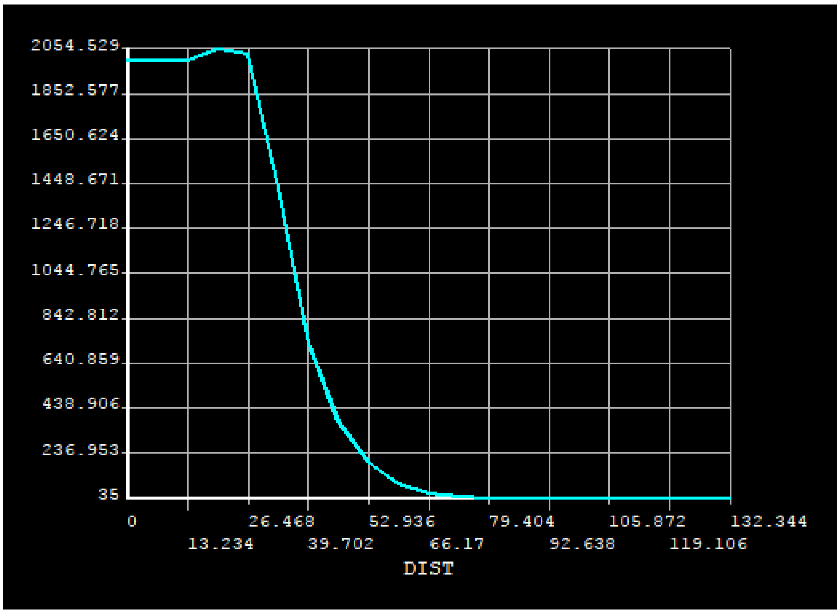

Figure 3.14. Figure 3.12: Temp(^{0}C) vs weld deposited(mm) plot for the element below top layer

The element in the middle layer was analyzed. The graph as shown below in Figure 3.15 describes a temperature graph which shows a drop in temperature for a certain period of time but due to the constant heat addition through the elements surrounding this element from all the sides and due to insulated base, the temperature of the element increases again. The elements transfer heat from the above and below layers to the element. Simultaneously, heat is also being taken away from the element through the convection process by air as well conduction to the elements at a lower temperature than the concerned element.

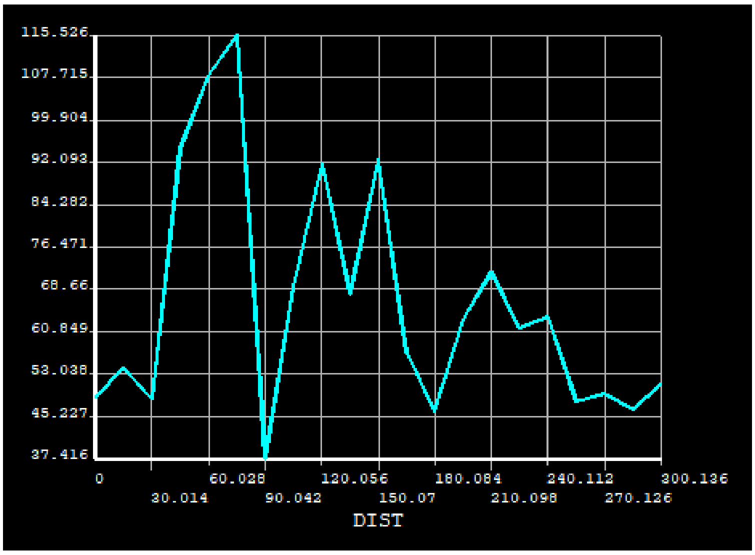

Figure 3.15: Figure 3.12: Temp(^{0}C) vs weld deposited(mm) plot for the middle layered element

The graph in the Figure 3.16 below shows the drop in the temperature of the element at the lower most layer of the component. It is in direct contact with the insulated base. This reduces the effect of cooling of the element. The heat transfer is dominant in this region. This leads to a very slow rate of cooling of the element.

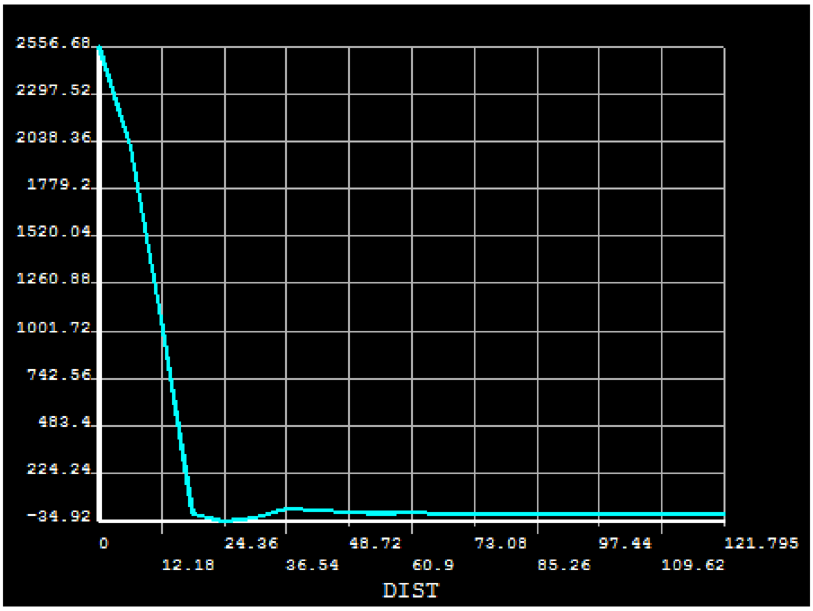

Figure 3.16: Temp(^{0}C) vs weld deposited(mm) plot for the lower most element

Chapter 4

Experimental Validation

The experimental setup for manufacturing of thin walled component was done using Cold Metal Transfer (CMT) for deposition of weld bead. The setup was done at IITH manufacturing lab. It also had CNC vertical milling center was setup at the center for obtaining a finished product. Figure 4.1 shows the CNC vertical milling machine for manufacturing of the product.

Fig 4.1: CNC machine used for additive manufacturing of the product

The weld bead is a function of the

(a) amount of current used to produce the arc,
(b) material of the wire used,
(c) diameter of the wire,

(d) speed of the torch movement along the weld bead deposition,
(e) speed of the wire at which it is consumed,
(f) the type and flow rate of shielding gas used to protect the slag formation against the atmospheric air and
(g) the gap between the nozzle and the base plate

These parameters were varied to obtain a stable arc with a good weld bead. The parameters used during the manufacturing process are as listed below in Table 3:

Table 3: Parameters for welding

Sr. no	**Name**	**Value**
1	**Wire material**	**0.8 mm ER70S-6 (copper coated mild steel)**
2	**Current (Amp)**	**95**
3	**Wire Diameter (mm)**	**0.8**
4	**Wire speed (m/min)**	**5.4**
5	**Torch speed (m/min)**	**0.3**
6	**Nozzle gap (base plate to torch)**	**10**
7	**Shielding gas flow rate (L/min)**	**8**
8	**Shielding gas used**	**82 % Argon + 18 % CO_2**

Thermal investigations were performed using the experimental setup for different cases. It was done to control the variation in the properties between layers being deposited and to control the surface modulations for a better finished product.

Different cases marked for the analysis were:

(a) Condition 1: The model has convective walls with a fixed base plate temperature)
(b) Condition 2: The model has convective walls with an isolated base plate)

The process is carried out by depositing the top layer of weld and letting it cool down to 93^0 Celsius before the next layer is deposited. The layers are deposited in alternative directions in order to nullify the effect of directionality and prevent formation of crater defects. The temperature measured during cooling of the weld bead is done at the midpoint of the thin wall deposited. Figure 4.2 shows weld bead being deposited layer by layer to produce the component.

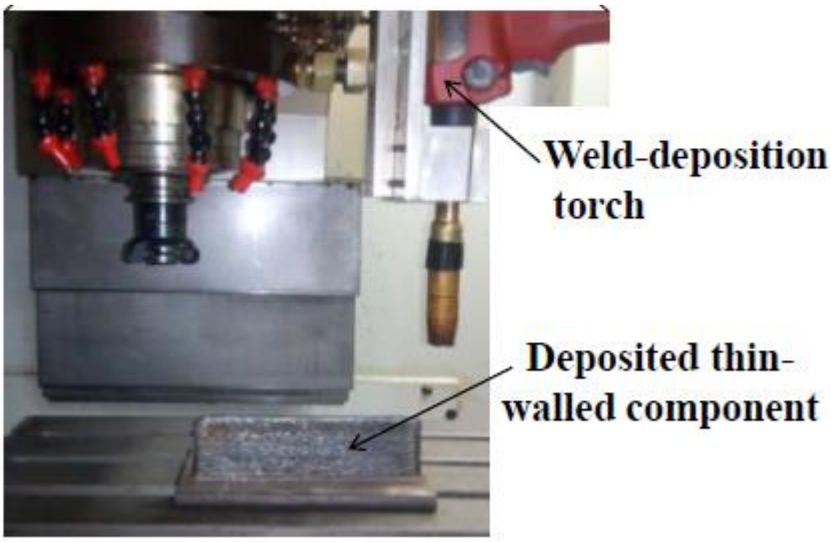

Fig 4.2: Manufacturing of the product by weld layer deposition

A finished product was obtained by milling the surfaces of the cooled product. Figure 4.3 shows the finished product. The experimental analysis reveals that the cooling methods affect the geometry of the bead resulting in modulations of the surface. Forced air cooling method resulted in high buy to fly ratio while that with conductive base resulted in lower buy to fly ratio.

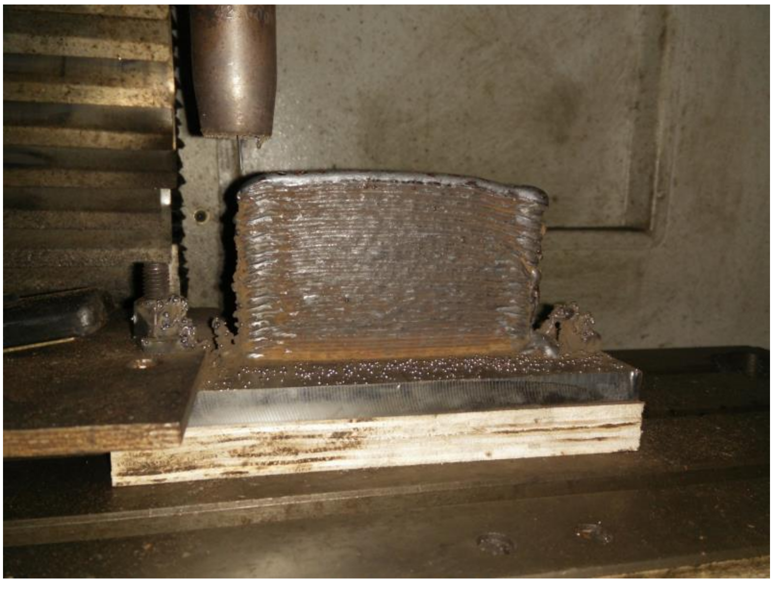

Figure 4.3: Finished product manufactured by additive manufacturing

A set of values was obtained for the cooling time of the layers with respect to the deposition of the weld bead was obtained for Condition 1 with the base maintained at constant low temperature and for Condition 2 with an insulated base. A graph as shown in Fig 4.4 shows a trend of the cooling of the welded layers at different conditions.

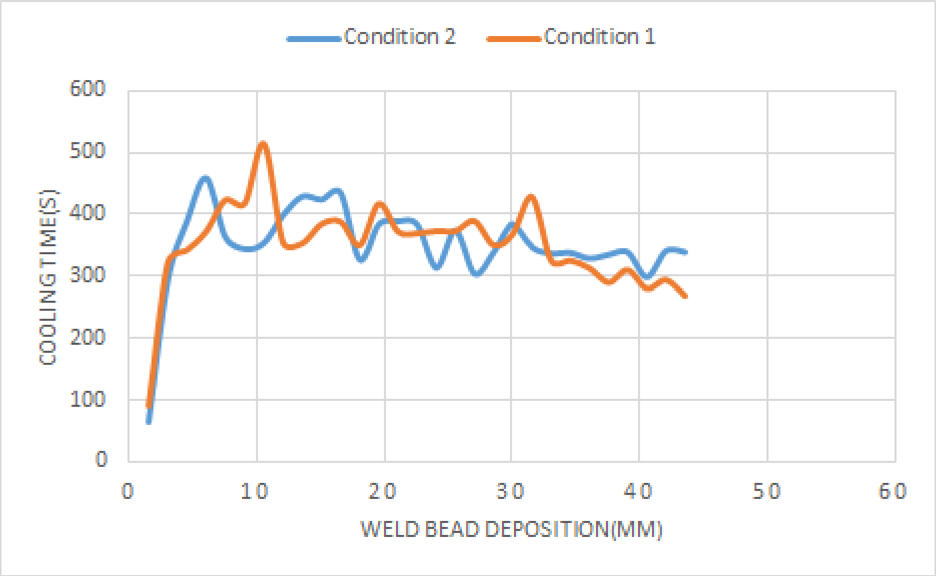

Figure 4.4: Time(s) vs Weld bead deposition(mm) in Condition 1 and Condition 2

By analyzing the graphs, it was observed that the pattern of cooling of both the model remained almost same. But the time taken by the insulated base to cool down was much higher than that of the model with constant low temperature base. This was because the temperature in the inner body of the work piece with insulated base was constantly high due to the continuous adding of heat through the weld deposition. This led to decrease in the rate of heat removal from the body.

The data of temperature obtained for measuring the temperature of the middle point of the layers through thermocouple of each layer was much higher as compared to the same point with constant low temperature base measured after the same duration of time. This gives a clear indication of heat being trapped inside the body of the component.

From the experimental analysis it was found that a pattern of cooling exists for both the models with certain percentage of error considering the practical implications and limitations of the problem. Graph between the time required for cooling of the weld bead with respect to the height of the weld bead deposited was plotted for simulated and experimental analysis. The graphs for Condition 1 and Condition 2 are as shown in Figure 4.5 and 4.6 respectively.

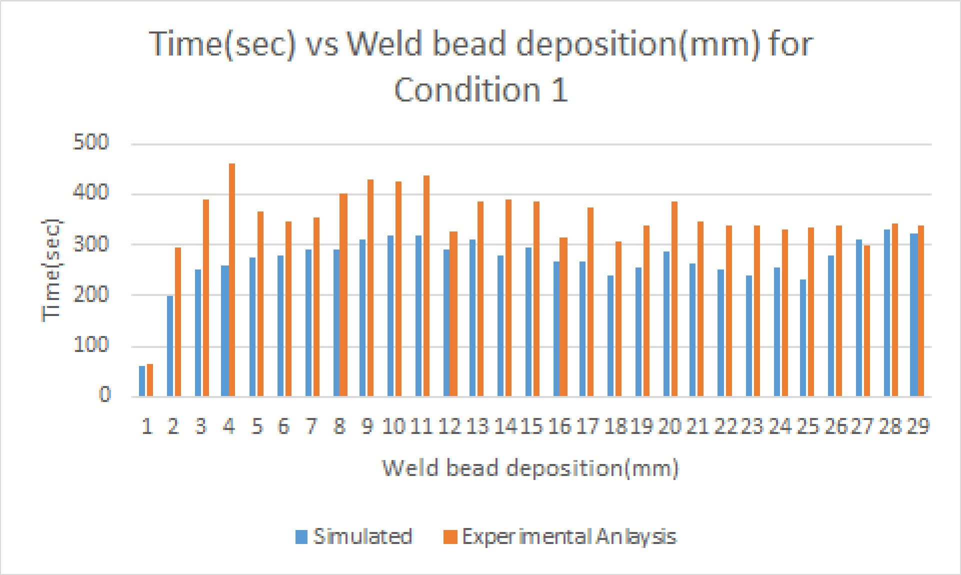

Figure 4.5: Time(sec) vs Weld bead deposition(mm) for Simulated and Experimental analysis in Condition 1

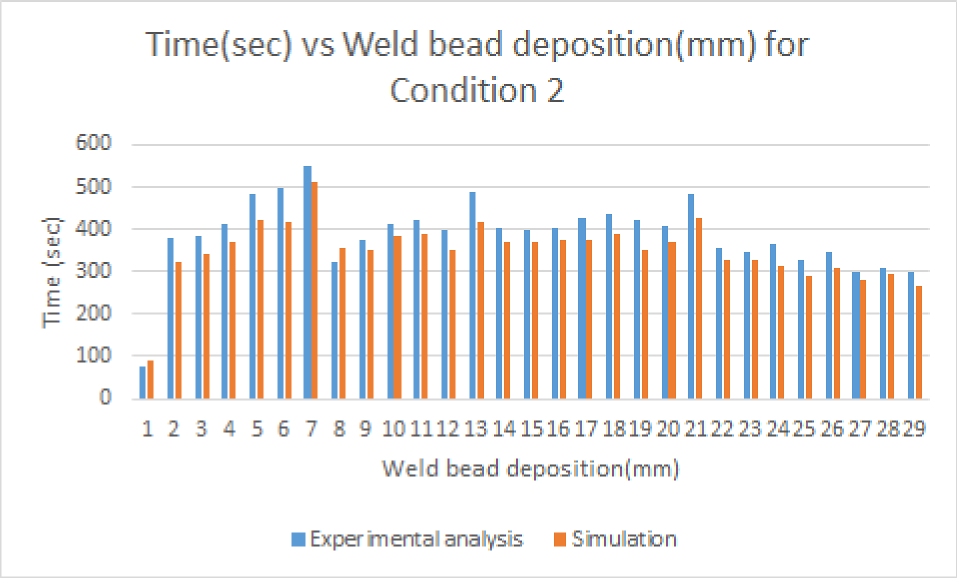

Figure 4.6: Time(sec) vs Weld bead deposition(mm) for Simulated and Experimental analysis in Condition 2

It was observed that the error percentage between the values exist but the trend of cooling of the welded component remains almost the same. It can be said that a general path flow of heat in the component is obtained according to which the cooling and heating of elements in the component take place.

Chapter 5

Conclusion and Future work

The simulation carried out was compared with the data obtained from the experimental setup for validation. It was found that the variation of temperature with respect to the distance of the weld bead as simulated in the software goes along with the trend of values obtained of the experimental analysis. The error percentage obtained was due to the practical problems during the welding process carried out in the experimental setup.

5.1 Conclusion

By analyzing the results obtained during simulation, a conclusion is obtained that the graph obtained for Model 1 gives a steady cooling rate of the component as compared to the graph obtained in Model 2 which gives an abrupt increase in the temperature of the component which eventually delays the cooling of the component.

This will eventually affect the grain structure formed in both the components. Model 2 grains will have more residual stress, being subjected to constant increase in temperature. As compared to this structure, the grains of the Model 1 will be more brittle.

The heat transfer figures obtained during the simulation show the transfer of heat taking place with respect to time and distance from the weld pool. This gives us a clear understanding of the path of flow of thermal energy in the models, which can be further used for analyzing the residual stresses in the component.

Graphs are obtained for different nodes undergoing heat addition and heat removal at the same time. The results show that there is a continuous change in the cooling pattern of each node and thus a mixed grain structure is formed after the weld is cooled down.

It is observed that there exists a variation in temperatures and structures at the end and the beginning of the weld bead but the middle layers tend to show a stabilized trend of stresses. The influence of complex distribution of stress, strain and microstructure results in a different type of properties of the component.

5.2 Future Scope

The model can be further analyzed for different types of coolants and their respective cooling rates. This will give a clear picture of the type of microstructure being obtained by the use of that specific coolant. A detailed study of the microstructure will help in the employment of the produced component as well as the reliability of the component produced in terms of its mechanical properties like fatigue strength, endurance etc.

A further study can be carried out to obtain the residual stresses in the component. This will help in identifying the weak areas of larger stresses in the body. Different methods of relieving the residual stress may be used and thus, accordingly the load can be applied on the component for its various use.

A study on the production of inclined components can be made in order to produce components with complex shapes as well as using multiple axes for the production of the component. Similar thermal analysis on these components can be very useful during the manufacturing and application of these components on wide scale. Manufacturing of complex shapes based on single bead weld deposition will not only reduce cost of resources involved but will also be useful for prototype development of various complex products being used in the industry as critical components.

The figures obtained for the variation of flow of heat with respect to time and distance from the weld pool gives us a clear understanding of the path of flow of thermal energy in the models. This pattern may be used to analyze the residual stresses in the component and treat the stresses accordingly to obtain a stronger structure.

A study on buy to fly ratio of the component can be performed to optimize the use of raw material. Buy to fly ratio refers to the ration between the weight of the raw material being used for the manufacturing of the component and the weight of the component produced. This will not only reduce the wastage of raw material, but will also improve the timing and effort required for the production of the component, thereby saving resources.

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