THERMAL STRESS ANALYSIS OF BUTT WELDED JOINT

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With profound sense of gratitude and regards, I would like to thank my family for their constant encouragement throughout my studies. Also I would like to thank my friends and classmates, who helped me in the course of the project.

ABSTRAK

Dalam kimpalan industri memainkan peranan yang penting di dalam proses penyambungan. Kebanyakan struktur kini dibina di roket ruang, dalam kapal selam menyelam dan kapal pembendungan yang sangat berat untuk reaktor nuklear tidak dapat telah dibina tanpa permohonan yang sepatutnya teknologi kimpalan. Ia adalah fakta yang diketahui bahawa semasa kimpalan logam di zon kimpalan mendapat cair dan kemudian keras, yang menyebabkan pengecutan dalam semua arah. Baki ketegangan dan tekanan pengagihan yang datang dari mengecut sebahagian besarnya dipengaruhi oleh sifat dan konfigurasi proses kimpalan, ciri-ciri logam kimpal dan bentuk geometri sendi kimpal. Ciri-ciri bahan terutamanya bergantung kepada kitaran sejarah haba melalui spesimen yang pergi melalui dalam proses. Jadi ini kitaran sejarah haba dikenali untuk mendapatkan pengetahuan yang lebih baik daripada fenomena kimpalan dan untuk mengurangkan risiko kegagalan.

Kerja ini menerangkan unsur terhingga terperinci prosedur untuk penentuan corak aliran haba dan agihan tegasan pada silinder yang dimodelkan dengan keluli tahan karat dan aluminium semasa kimpalan. Dalam hal ini, Modified Double Pengagihan Corak elipsoid telah dimodelkan dan dipertimbangkan untuk reka bentuk lopak kimpal. Sifat bahan Elasto plastik pada suhu pelbagai juga dianggap untuk simulasi. Satu kelajuan kimpalan boleh ubah telah digunakan semasa kimpalan dan kesan kelajuan kimpalan tak lelurus juga dikaji. Sementara sejarah haba di pelbagai tempat telah ditentukan dan dibandingkan dengan data yang diterbitkan disediakan. Lengkung penyejukan boleh diperolehi dari rantau menurun sejarah Transient lengkung haba di pelbagai lokasi. Dengan ciri-ciri ini metalurgi bahan di zon kimpal dan haba zon terjejas boleh diperolehi semasa proses simulasi kimpalan. Masalah pengagihan penyelewengan dan tekanan telah juga dijalankan. Satu pengaturcaraan khas telah dibangunkan untuk simulasi kimpalan.

ABSTRACT

In industries' welding plays a vital role in joining process. Many of the structures presently built in space rockets, deep diving submarines and very heavy containment vessels for nuclear reactors could not have been constructed without the proper application of welding technology. It is well known fact that during welding the metal at the welding zone gets melted and then solidifies, which results in shrinkage in all the directions. Residual strain and stress distributions coming from shrinking are largely influenced by the nature and configuration of the welding process, metallurgical characteristics of weld and the geometrical shape of the weld joint. The material characteristic mainly depends on the thermal history cycle through which the specimen goes through in the process. So these thermal history cycles are to be known in order to get a better knowledge of the welding phenomenon and to minimize the risk of failures.

This work describes the detail finite element procedure for determination of heat flow pattern and stress distribution on cylinder modeled with stainless steel and aluminum during welding. In this, Modified Double Ellipsoidal Distribution Pattern was modeled and considered for the weld pool design. Elasto-plastic material properties at various temperatures were also considered for simulation. A variable welding speed was used during welding and effect of the nonlinear welding speed was also studied. Transient thermal histories at various points were determined and compared with available published data. The cooling curve could be obtained from the descending region of the Transient thermal histories curve at various locations. By this metallurgical characteristic of the material at the weld zone and heat affected zone can be obtained during welding simulation process. The problems of distortion and stress distribution were also carried out. A customized programming was developed to for the welding simulation.

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LIST OF ABBREVIATIONS

I	*Welding current, Amps*
V	*Voltage, Volt*
η	*Welding Efficiency*
A	*Semi Major axis of ellipsoid in X-direction, m*
B	*Semi Major axis of ellipsoid in Y-direction, m*
C	*Semi Major axis of ellipsoid in Z-direction, m*
	C_f *– for front Ellipsoid*
	C_b *– for rear Ellipsoid*
$r_{(f,b)}$	*Correction factor to merge both the Ellipsoid at Z=0.*
X_o, Y_o, Z_o	*Fixed Coordinate System*
X, Y, Z	*Local or Moving Coordinate System*
L	*Length of the specimen, m*
W	*Width of the pipe, m*
T	*Thickness of the pipe, m*
K_{eff}	*Effective thermal conductivity W/m-K*
Q	*Double ellipsoidal heat source model* W/m^3
Q_m	*Maximum heat source applied on the Pipe* W/m^3
Q_{eff}	*Effective heat source on the finite pipe* W/m^3
Cp	*Specific Heat in J/Kg-K*
P	*Density of the material in* Kg/m^3
L	*Lantern heat in* J/m^3
TIG	*Tungsten Inert Gas Welding*

CHAPTER ONE: INTRODUCTION

1.1 Introduction

In industries, welding plays an important role in joining process. Many of the structures presently being built in deep diving submarines, space rockets and very heavy containment vessels for nuclear reactors is constructed with the proper application of welding technology. Welded structures are superior in many respects to riveted structures, castings and forging. Welding has many advantages over the other joining methods as given below.

- The welded structures have high joint efficiency.
- The weight of a ship's hull structure can be reduced as much as 10 to 20% if welding is used.
- Joint designs in welded structures can be much simpler than those in riveted structures.
- The welded structure has reduction in fabrication time and reduction in cost also.

Welding is used in the fabrication of buildings, ships, oil-drilling rigs, pipe lines, rockets, space crafts, nuclear and pressure vessels mainly due to the above said reasons.

After welding operation the next step is to cool the molten. Cooling of molten is done by shrinking in all the main directions. Residual strain and stress distributions are obtained from shrinking. These stress and strain are largely influenced by the metallurgical characteristics, geometrical shape, nature and configuration of the welding process. This stress and strain will lead to a crack occurrence, stress corrosion, deformation, loss of mechanical characteristics, and loss of interchangeability. Hence residual stresses have to be studied so as to get a better knowledge on the steps to minimize risks.

Prediction of welding residual stresses helps to prevent failure and also to optimize welded structures. Hence, in industries calculating welding residual stress is given importance in recent days. In the case of pipe structures cir-seam welding can generate cracks across the welds. The reason for this cracking is due to the stress corrosion of stainless steel. This is mainly because of welding residual stress, in the presence of corrosive atmosphere.

1.1.1 Butt Weld Joint,

Joining the two metals by using welding along the edge of the metal in single plane. Welding can be done on many type of material . Most commonly used in Joining metal and thermoplastics. Butt welding can be done on joining metal, joining the pipe which is used commonly in fabrication of bank tubes, economizer Tube, Super heater Tubes, During Welding, Two metal which is to be joined together will be heated to melting zone then Tungsten filler metal is filled between the joint. After heat source is stopped, the liquefied metal and also filler metal will start cooling immediately. They will make a bond together.

There are many type of butt-weld joint. They are Single Square joint, Single-Bevel, Double-bevel, Single-V , Double-V, Single-U, Double-U, Single-J, Double-J and Flange Joint

1.1.2 Application of Stainless Tube & Aluminum Tube

Stainless tubes and aluminum tubes are used in power plant to transfer the heat sources to get the steam. Aluminum tubes are used in Plate heat exchanger where heat transfer occurs. Other application of the aluminum tubes and stainless tubes are used in Liquid process Cooling, Cooling water in Chemical Plant, Petroleum and Petro Chemical Industry.

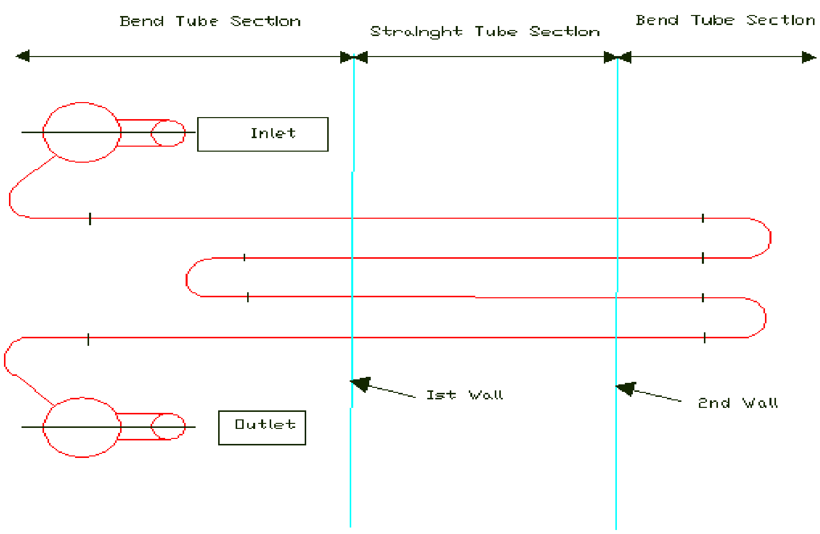

Figure 1.1 Super Heater tube in Waste heat Recovery Boiler

1.1.3 Finned tubes

Figure 1.2 Finned Welded with Pipe in Super Heater

In boiler industries to get more heat area finned tubes are used in Economizer Air heater,super heater and Bank tubes. Depending the service temperature Stainless tube with stainless fin and stainless tube with aluminum fin is used.

1.1.4 Failure butt welded Joint in Industry.

Due to residual stress after welding will propagate crack on the welding which leads to leakage on the joint. Depending the services on the pipe, The problem may come bigger or smaller while leakage . Result of solidification and cooling residual stress formed on the weld joint due to weld shrinkage.

Because of welding deformation will occur as strain. If the deformation(contraction) is restricted will cause the residual stress permanently in the weld joint. This residual stress will create crack on the weld joint.

Large weld size and deep penetration of weld will create shrinkage strain. This will create residual stress on the weld. Due to this strain will increase the yield strength of filler metal and base metal. So Higher Yield strength will create higher residual stress on the weld joint.

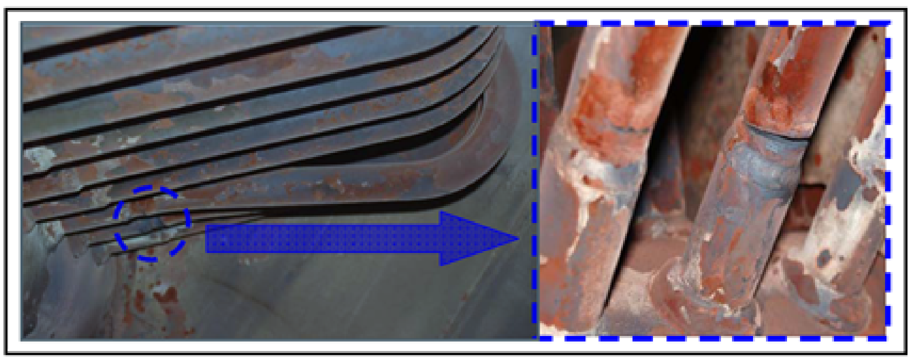

Figure 1.3 Butt Weld Joint Failure in Boiler Plant

1.2 Objectives and Scope of work

The main objective of this project are given below

(i) Improvement of Heat source modeling to match with actual working condition.

(ii) Welding simulation (thermal analysis) of a butt welded pipe illustration.

(iii) Mechanical analysis to estimate the residual stress and distortionComparison of (ii) and (iii) for aluminum and stainless steel material.

1.3 Thesis Outline

Chapter 1 covers the introduction of Stress analysis of Stainless steel in welded zone. Also, this chapter explains about the main objective of the research project.

Chapter 2 covers background of study; discuss about the existing welding techniques and the theory of heat flow which is essential for the study of welding process analytically and numerically.

Chapter 3 provides a brief presentation of the theory of TIG welding and its heat effects on the base material.

Chapter 4 provides details about Goldak equation used for modeling the heat source input.

Chapter 5 provides Finite element modeling and analysis procedure. Also, this chapter explains about the assumption made for doing the analysis

Chapter 6 provides details about the flowchart and final results.

CHAPTER TWO: LITERATURE REVIEW

2.1 Introduction and Background

Welding simulation is started in research activity by Rosenthal on 1947 first. He developed analytical solution for heat flow while welding. This analytical solution can be used to justify the 2D and 3D weld pool. It is important to understand how the heat flow acting in analytical, experimental and numerical. From Rosenthal consideration of heat flow, Many researchers considered the heat flow while welding. That will reviewed below in this chapter.

[1] Mr. G. Ravichandran has done Finite element analysis to Justify the thermal cycles in welding zone. He mainly concentrated on Gaussian distribution to do transient Analysis on welded pipe. That simulation was validated by experiment also. He justify the thermal cycle has major role on weldment. So **he concluded thermal cycles are very important in welding zone.**

[2] E.A BONIFAZ, concentrated on heat equation to justify how much heat is available by an arc in terms of heat energy. He derivation the heat equation with the input of heat flux per unit area, thermal conductivity of material , heat energy input per unit time. To get the actual welding in model he utilized the heat input and thermal conductivity to get close to match the welding in actual condition. For that he **used COSMOS in Finite element code for simulation.** In arc welding heat penetration is lesser than high density welding like LBW , EBW. So he used **Gaussian function to simulate the heat model** for lower penetration in the welding. Double Ellipsoidal can be got while using LBW and EBW process in Finite element method. So he conducted the simulation by using Gaussian method is nearly to the

actual model which is using double elliptical heat source dimension. And also this COSMOS code was integrated with Navier-stroke hydrodynamic equation. Because of the less heat penetration Gaussian function was used

[3] S.B.BROWN AND H.SONG did research on large welding structures during welding. He was doing research on residual stress and distortion on big welding structure during welding. They both concluded that it was difficult to simulate the actual welding in big structures in the model . The final state of residual stress and distortion will be because of significant effect of local welding zone and surrounding structure. They feel difficult to simulate such a complexity**. They conclude while welding thermal expansion of structure and elastic constraint by structure will have influence in weld**.

[4] G. Ravichandran has done research by writing C language package to do finite element method on thermal cycles in tungsten pulsed gas arc welding. He got the result at regular interval of time. **Finally he concluded that Two Dimensional model will be enough to get the temperature distribution on the welded zone** and the result of distribution is fluctuates while pulsed welding even after the arc crossed.

[5] D.Rossenthal did research Two dimensional and Three dimensional finite element method to get moving heat source on welding the steel. He has given the solution for linear transition heat model. This solution can be applied on the welding problems. He explained the fundamental theory for the solution in welding problems. He mainly concentrated to find the**rate of cooling with respect to timing which has got good accuracy with varying range of** temperature and condition of welding including wide variety of thickness for the steel.It was showing good result to the actual welding. He has found a single formula for predicting the cooling rate with range of temperature.

[6] M.R.Frewin and D.A. Scott did research on Three dimensional Finite element model of heat source which pulsed laser welding beam. ANSYS code was used to define the heat source in modeling. He got the temperature result after welding in the affected heat zone. He utilized radiation and convection in lumped transfer of heat co-efficient. When the model was sectioned for FZ and WZ , he got result time history. **The heat source was modeled as three dimensional weld. He concluded the to do model the heat source NASTRAN, ABAQUS to** get the correct mesh and re-meshing scheme. He got the result after modeling was temperature transient profile as well as heat affected zone dimension.

[7]Min Jou did research on process of GTA welding. He has given the temperature distribution at different welding condition. He has developed 3-D model of different condition of welding. He carried out for the thickness 4mm and 6mm with welding speed varying with numerical method. He find$r_o$of heat distribution has got good influence on the dimension of weld pool. While increasing the $r_o$weld of the top surface in the weld. It will get round shape to tear the drop shape. While rear end r_o increasing the weld pool depth direction decreases. Due to the weld size changes the efficiency will get changed which is related directly to input of heat. While changing the length of top surface and width of top surface of the weld the efficiency is also get changed. While decreasing the r_o the cooling rate will be quickly possible.

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[8] Dr. Adman , Dr. Nabeel N. JameelK.Abid Al-Sahib F.Abd Al Latteef , Dr. Osama did research on flat joint weld in thing pipe. They studied numerically and analytically on the joint. In analytical method he has got good result of residual stress formed in the thing pipe welding after shrinkage of weld. In numerical method he has got good result of non-linear heat transfer transient . He has given the input of ambient and heat source. He was using

ANSYS 8 version to find the simulation weld pipe to get distribution of temperature and stress analysis. He used the same programming before and after welding to justify the stress formed on the piping.

[9] C.M. Chen ,Kovacevac did research on stir welding of friction of modeling by finite element method. Tool mechanical reaction and material of thermo properties was incorporated in the model. During welding residual stress of weld was measured in X-ray technique of diffraction. During friction when slides tool on work page , the heat is generated which was given in the model to decide the residual stress. The other property of the material of elasticity , plasticity was also considered. In analysis dependant properties of temperature was used. The heat source was modeled as moving on the friction zone of tool and work page in each node. Due to the heat source the material properties will get change which is coupled to get the thermal parameters with incremental of time.

[10] A.K. Pathak, G.L. Datta did research on welding zone with arc length changes. He model finite element analysis of three dimensional transient as well as heat flow. He has given the input for solid phase and liquid phase of welding during fusion by changing the enthalpy. He has used the Gaussian method to get the distribution by arc. The molten zone also was modeled as temperatures input into the node when exceeding the melting point. He has used ANSYS 5.0 for the finding the solution. He concluded by varying arc length can change the effect of molten pool temperature and base material.

[11] B. Tanjat, T.Zacharia did research on spiral cladding of weld by using the finite element method. By using this they found the solution to justify the residual stress on the clad tube of weld. They simulated the symmetric of cladding process of weld. They developed two

separate solution for the justifying mechanical and thermal of weld clad process by two runs of welding simulation. They found more residual stress on outer surface and less residual stress on inner surface of weld cladding. They developed Neutron diffraction of technique was modeled to find the stress of residual in the tube of clad. But they have not modeled the electrode waving as ABACUS FEA code for weld bead and width.

[12]MAN GYUN NA , JIN WEON KIM AND DONG HYUK LIM did research on welding by using Fuzzy Neural Network model. He got the residual stress at welding condition varies. He developed the solution model by using algorithm to limit function of the membership parameters as well as to get solution of consequent parameters. Fuzzy Neural model of network is a hybrid method. It was separately into four groups .First two for End-section constraints and other two for Prediction of paths. By using this model we can get numerical data of finite element method of two end-section and two prediction paths. He concluded the accuracy of this model to justify the residual stress on dissimilar metal welding.

[13] S.H LEE . Y. S YANG did research on welding of thermal system by varying design parameters. Heat flow on the welding is analyzed in laser treatment surface. He developed sensitivity analysis of direct differentiation method. The main parameter considered in the analysis was radius. By using Gaussian method the heat source was modeled to get the distribution of temperature of transient condition. He develop quasi-stationary condition to model the heat source as moving system of co-ordinate with constant speed.

[14] H.RUNNEMALM, S.HYUN did research on three dimensional welding. He used adaptive mesh scheme. He has reduced the computer timing by coupling thermo mechanical analysis. He explained the generic posteriori formulation of error which helps to find the

thermal distribution and mechanical distribution. He conclude creating mesh will give good result of accuracy on computational effort.

[15] N.T. NGUYEN did research on three dimensional finite analysis by using moving heat source. He used ellipsoidal one to find the solution as heat source model. He has taken weld plate as specimen for analysis. He did experiment for different heat source model. He found effect the heat source model for all the cases. He concluded the analysis result and suggested and briefed about the thermal analysis modeling , structural analysis modeling to find the residual stress and distortion in process of welding

[16] ELIJAH KANNATEY - ASIBU did research on thermal equation finding heat distribution. He found solution for latent effect heat. He developed technique of numerical with redefined mesh in computational time. Basically this technique was developed for 2-dimension. For this adaptive mesh was been developed in element method. This result was considered comparing the temperature distribution in all welding conditions.

[17] P. TEKRIWAL , J . MAZUMDER did research on thermal and mechanical analysis. He developed 3-dimensional finite element method to show the arc for the welding. He has developed Gaussian numerical method to model the heat source as well as convection heat transfer. He has taken the accountability of gas shielding effect. This Gaussian method is developed in ABAQUS stress analysis. He found the temperature quickly changed while initial time of heating. He suggested the cooling process to decrease by increasing the timing. He has considered baushchinger effect for von misses criterion.

[18] G.W. KRUTZ, L.J. SEGERLIND did research to develop finite element method resulting time history of welding joint. He developed the method to optimize the joint of strength. At zero-volume point the heat has been concentrated in the model as area or line. The heat of solid phase and liquid is been given as latent heat. If the metal is not alloy the

phase change will take at defined temperature. And he found the filler metal adding will have significant effect on weld zone. That is not been modeled due to difficulties. This model is mirror type. So one part was modeled and analyzed. To match the actual welding non linear analysis was done in finite element model. He found the changes when arc length was changed.

[19] W. G. ESSERS, R. WALTER did research on penetration in total area of cross section during welding. He considered the depth of welding and develop electromagnetic method by filling the filler metal in a determined direction. When the filler drop at point on which penetration required. While transferring the filler metal drop on the work piece which was heated more. This more heat will fusion the metal to be welded. He found the depth penetration by experimental. From these value how much heat is used in filler drop which penetrate the metal. He found about 35% of heat is transferred to work piece to be welded in GMA welding.

[20] A. TAYLOR, M.HUGHES, did research in welding of frame work by using numerical work frame of fluid dynamics and solid computational mechanics. This CFD modeling of fluid dynamic in weld area , change of heat and change of phase . For this centered cell volume of finite method was used. He has developed alternative vortex using FV based on elasto-plastic deformation using CSM. And also he developed PHYSICA for the measurement of unstructured measures.

[21] X. SUN did research on Electrical-Thermal-Mechanical analysis. He did simulate the welding process by projection. Due to changes of heat path and current variation it is difficult to model in simulation. And also due to changes of material properties based on temperature variation, it is difficult to model to simulate. So he did modeling using collapse mechanism and he suggested the process formation and welding parameters change with work pies to be

welded. So he developed Fortran program making link with ABAQUS to different analysis of modules. He found that it is difficult to obtained correct simulation while projection welding as well as spot welding.

[22] Z. CAO, Z. YANG, X.L. CHEN did research on fluid model with three dimensional fluid. It can do analysis flow effect of droplet in weld pool penetration in weld profile bead as well as radius on toe. He simplified the model adding the laminar flow and compressible flow as well as Newtonian through the terms of buoyancy terms. The arc shape depends on the heat, flux as well as current. He did some practical experiment. Then he compared the simulated model with actual model. It briefly describe the filler metal drop while heat dropping on the work piece.

[23] K. S .YEUNG , P.H. THORN TON did research on spot welding electrode. He developed a model to justify the thermal analysis in spot welding. He developed the technique that was used for heat transfer value co-efficient while analysis will rise. He combined heat energy of convection and conduction as model which rotates during welding. For example heat transfer problem in classical the boundary condition is applied as convection heat energy with varying convection co-efficient. It is done in ANSYS and been meshed in FLOTRAN

[24] C. L .TSAO. S.C. PARK, W.T. CHENG did research on mechanism of distortion in sequence. He found during weld by simulation the local plate was buckling as well as bending in finite element method.

[25] C. –H. Lai and their colic's did research on arc-welding non linear two dimensionalsimulation. They consider temperature dependant of material properties non uniform energy distribution and phase change from the heat source. He model the heat source

moving on the boundary. He found the solution which solve the problem efficiently on certain circumstances.

[26] RICHARD E. AVERY did research on dissimilar metal welding. He formed the metallurgical base how to weld. The metal of dissimilar was weld easily in fusion weld and low weld of dilution. Low weld of dilution was used in mass production. He considers wide variety of dissimilar metal in finite element analysis as well as concentration of electrode.

[27] R. KOMANDURI and Z.B. HOU did research on arc welding. He found how the thermal properties of metal with respect to temperature was getting changed. He aimed to select correct thermal properties to be applied during arc welding.

[28] PENG ZHANG, LINPO SU, XIANCHUM LONG AND YONGHONG DUAN did research on V girth welding on piping. He developed 3D mesh in finite element analysis considering weld temperature. He summarized on varies inner surface pressure 0MPA, 5MPA, 10MPA ,15MPA with finding variation of residual stress forming during welding.

[29] DUNCAN CAMILLERI, TOM GRAY did research on fusion welding using infrared thermograph to find the temperature of transient heat. By simulation he try to find the actual data which can be given for calculating computational simulation of welding during manufacturing process. He has given the comparison of welding large structure as thermo graphic data in finite element method

[30] IHAB. F. Z. FEANOUS, MAHER. Y.A. YOUNAN, did research on material deposition during welding by using element birth method. By using this method with quick time we do analysis of 3D problem.

CHAPTER THREE: TIG WELDING THEORY

3.1 Principle of TIG welding

The TIG welding process was invented during the Second World War in American aircraft industry. This was invented for joining magnesium and Aluminum. TIG welding process was first demonstrated by Russell Meredith [61] in 1930. TIG welding is also called as GTAW (Gas Tungsten Arc Welding which is the common name in North America). It uses a non-consumable tungsten electrode protected by an inert gas. Schematic representation of TIG welding is presented in Figure 3.1.

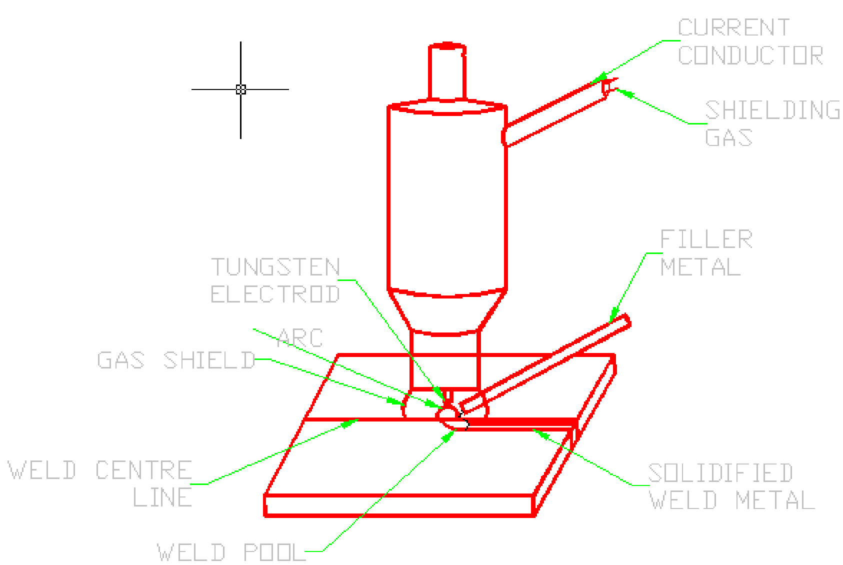

Figure 3.1: Principle of Tungsten Inert Gas (TIG) welding.

A Plasma arc is generated by the electrical discharge. The plasma arc is initiated from a high frequency generator.The frequency of this ignition pulse is large, up to several MHz. This frequency produces strong electrical interference along with high voltage of several kV. This electrical interference is produced around the welding cell.

Three different alternatives of current can be used namely; direct current (DC) with a positive electrode, DC with a negative electrode or alternative current (AC). Alternative Current is mainly used for the welding of aluminum and magnesium. This is mainly because of the cleaning of oxide layer on the surface. Most other materials use Direct Current with a negative electrode.

3.2 Process parameters of TIG welding

TIG welding process is defined in three main parameter groups. This is shown in figure 3.2. The first group is the group of controllable process parameters [15]. The second group has the control of the process and consists of sensor variables. The sensor variables are used for the supervision.The third group comprises of final weld characteristics.

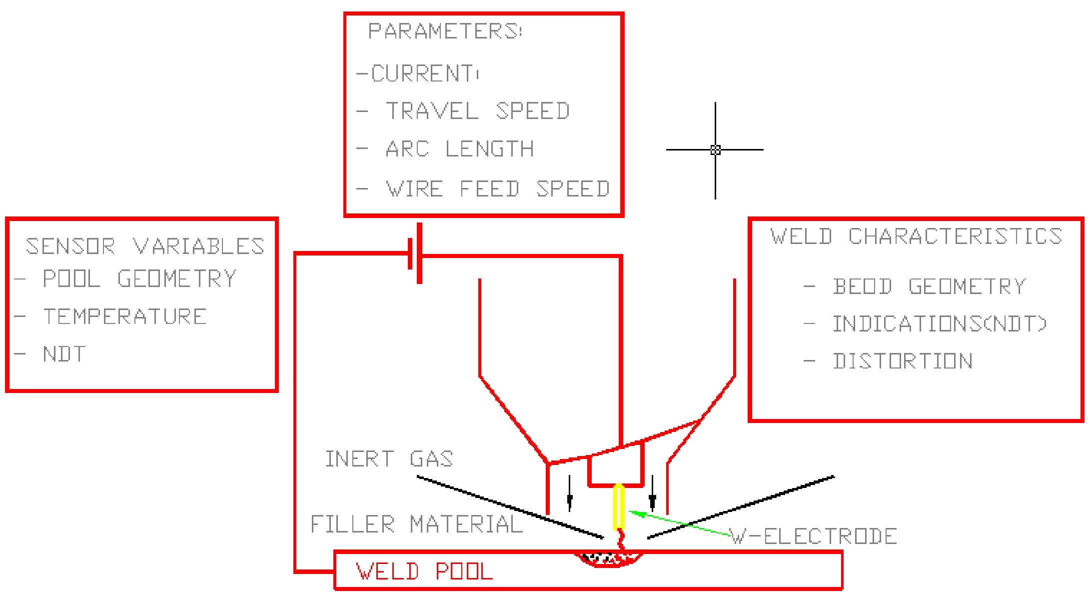

Figure 3.2: Schematic diagram of the TIG process with its three parameter groups.

Schematic representation on weld characteristics of two butt welded plate [17] is shown in figure 3.3 and a real cross-section for butt-welded plate is given in figure 3.4.

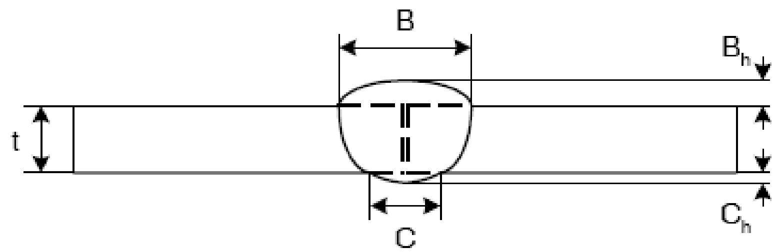

Figure 3.3: Weld characteristics for two butt-welded plates with thickness t.

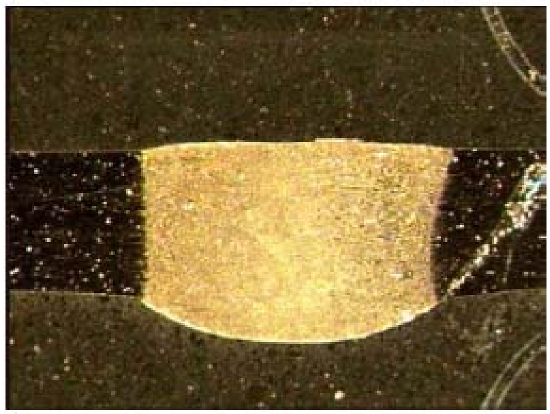

Figure 3.4: A typical cross section of a weld.

3.3 Heat effects of welding

Heat transfer phenomena play an important role in welding. Heat effects of welding indicate temperature fields, residual stresses and distortion that occur during or after welding.

3.3.1 Temperature fields

The main objective in heat transfer analysis is to determine the temperature fields in an object [18]. Temperature distribution normally represents the variation of temperature within position in the object. After calculating Temperature distribution the conduction heat flux is to be calculated. The conduction heat flux can be obtained from Fourier's law.

The below properties are needed for thermal analysis

- Conductivity
- Specific Heat
- Latent Heat
- Density

The basic equation for thermal analysis is shown below

$$q = -\lambda \frac{\partial T}{\partial n} \quad (3.1)$$

Here

- λ is the thermal conductivity
- *T*is the temperature.

The Taylor series expansion after neglecting higher order is given below

$$qx + dx = q + \frac{\partial qx}{\partial x} dx \quad (3.2)$$

Here, *dx* is a small control volume and$q_x$is the heat rate at the control area. Energy source term (3.3) and an energy storage term (3.4) in the control area can be given as below

$$\dot{E}_g = qdx \quad (3.3)$$

$$\dot{E}_{st} = \rho C_p \frac{\partial T}{\partial t} dx \quad (3.4)$$

Reducing the above equations,

$$q_x + qdx - q_{x\text{-}dx} = \rho C_p \frac{\partial T}{\partial t} dx \quad (3.5)$$

Equation 3.2 and Fourier's law can be written in a general form as below,

$$\frac{\partial}{\partial x}\left[\lambda(T)+\frac{\partial T}{\partial x}\right]+\frac{\partial}{\partial y}\left[\lambda(T)\frac{\partial T}{\partial y}\right]+\frac{\partial}{\partial z}\left[\lambda(T)+\frac{\partial \mathrm{T}}{\partial Z}\right]= \rho Cp(T)\frac{\partial T}{\partial t}-Q \quad (3.6)$$

Where, x is the welding direction,y is the transverse direction, and z is the normal direction to weld surface.

The initial conditions are given below

$T=T_o$ at $t=0$

A general boundary condition is given below

$$\lambda\frac{\partial T}{\partial x}lx+\lambda\frac{\partial \mathrm{T}}{\partial y}ly+\lambda\frac{\partial \mathrm{T}}{\partial z}lz-q+h(T-T\infty)=0 \quad (3.7)$$

Where h is the surface heat loss coefficient, T is the surface temperature and $T\infty$ is the environment temperature.τ is used to determine whether the plate is to be considered as thin or thick. In a thick plate the heat flow is considered to be three dimensional. The thin plate equation can be applied if the heat flow is needed in lateral direction.

$$\tau = h\frac{\sqrt{\rho Cp(Tc-To)}}{Hnet} \quad (3.8)$$

Where, h is the plate thickness. $H_{net}$is net energy, $T_o$is the initial pipe temperature, $T_c$is the temperature. From T_c the cooling rate is calculated. The pipe is considered to be thin if ζ is less the 0.75 and is thick if ζ is larger than 0.75.

$$r=\sqrt{\xi^2+y^2+z^2} \quad (3.9)$$

Where, ξ is given by equation (3.10)

$$\xi = x-\upsilon t \quad (3.10)$$

ξ, y , z are the origin of the moving coordinates and the moving coordinates are fixed at the centre of the heat source. This is shown in figure 3.5.

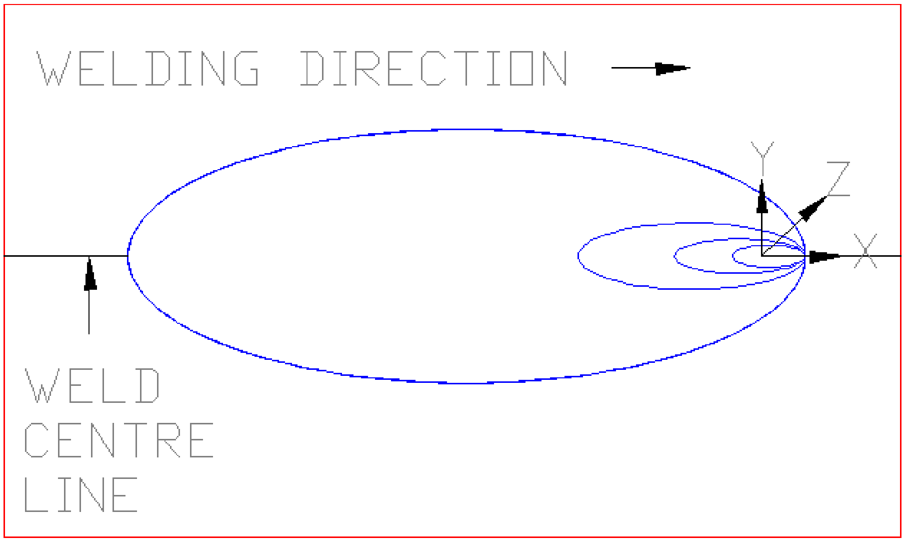

Figure 3.5: Schematic of the welding thermal model.

For a thick pipe

$$T-T_o=\frac{q}{2\pi\lambda r}e[\frac{-\upsilon(\xi+r)}{2K}] \quad (3.11)$$

For a thin pipe

$$T-T_o=\frac{q}{2\pi\lambda d}e\frac{-\upsilon\xi}{2d}Ko(\frac{\upsilon r}{2d}) \quad (3.12)$$

Figure 3.6 gives welding parameters on temperature. Top left figure shows the welding speed at 2.0 mm/s, topright shows the welding speed at 3.0 mm/s, Low left shows the welding current at 100 A and the low right shows the welding current at 80 A.

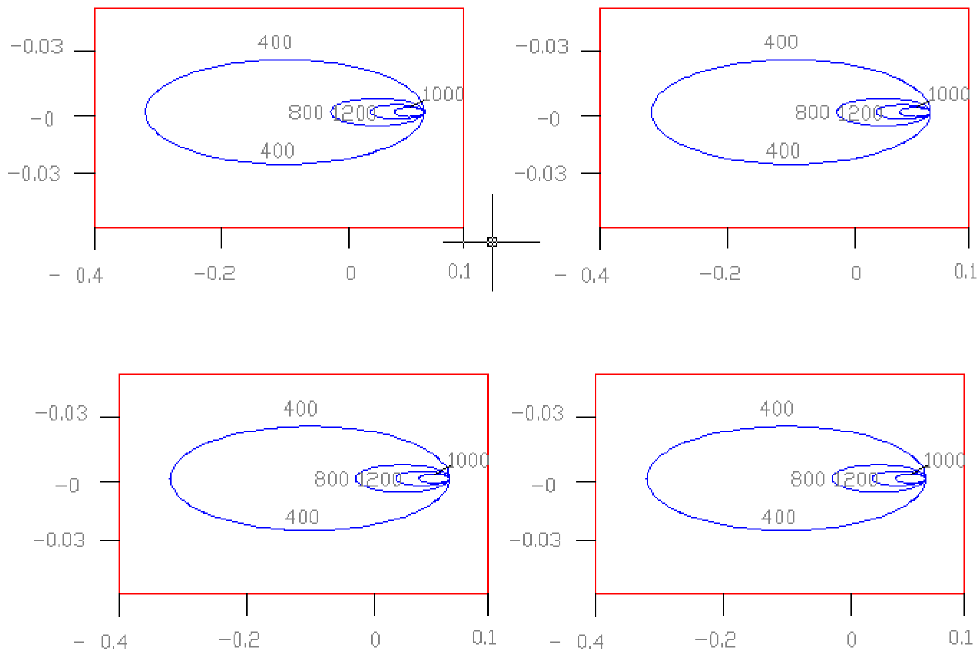

Figure 3.6: Temperature contour plots with different welding parameters.

Figure 3.7 shows a plot of time Vs temperature and also indicates the peak temperature cooling rate.

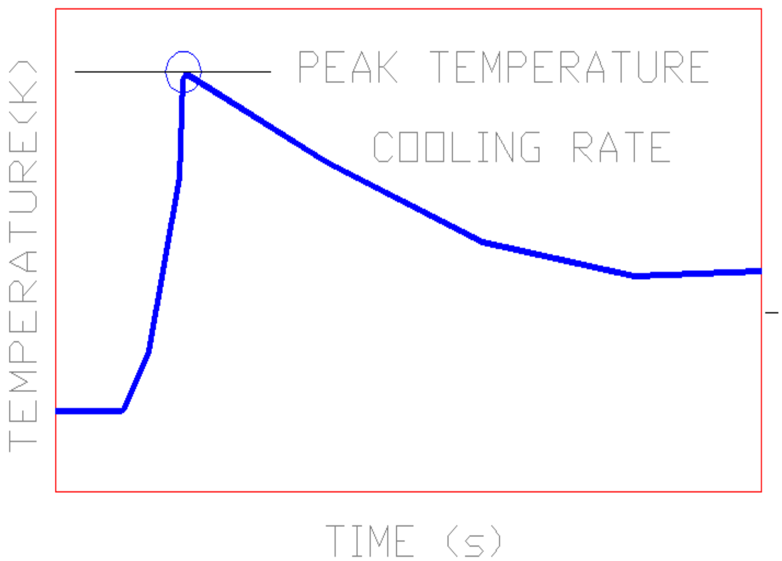

Figure 3.7: Important temperature characteristics.

The peak temperature [2] is given by equation (3.13)

$$\frac{1}{Tp-To}=\frac{\sqrt{2\pi e\rho}\ \mathrm{CptY}}{\mathrm{Hnet}}+\frac{1}{Tm-To} \tag{3.13}$$

Cooling rate can be defined for both the thick plate and the thin plate and is given in equation (3.14) and (3.15) respectively,

$$R=\frac{2\pi\lambda(Tc-To)^{3}}{\mathrm{Hnet}} \tag{3.14}$$

$$R=2\pi\lambda\rho Cp\left(\frac{\mathrm{t}^{2}}{H\mathrm{net}^{2}}\right)(Tc-To)^{3} \tag{3.15}$$

Where, R is the cooling rate and $H_{net}$is net energy input.

The solidification rate has an effect on the material properties and is given by the equation (3.16)

$$S_t=\frac{LHnet}{2\pi\lambda\rho Cp(Tm-To)^{2}} \tag{3.16}$$

Where, L is the heat of fusion.

3.4 Residual Stress

For residual stress analysis, some properties such as Elastic modulus, poison’s ratio, Yield stress and density are required. Deformation above melting point does not affect the residual stress since the molten material re-solidifies. Hence material properties up to melting point are needed for the stress analysis.

3.4.1 Residual stresses and distortion

Heat transfer analysis should be done first to evaluate thermal stress. After that non linear structural analysis was done using temperature distributions.

Quasi static equation is given in equation (3.17)

$$\nabla \sigma + F = 0 \qquad (3.17)$$

Where

∇ is the differential operator

σ is the stress and

F is the body force.

The stress strain relationship is given in equation (3.18)

$$\{\boldsymbol{\sigma}\}=[D]\,\{\xi\} \qquad (3.18)$$

Where

$\{\sigma\}$ is the stress vector

[D] is the stiffness matrix

$\{\xi\}$ is the strain vector

Elastic strain is given by

$$\xi_{elastic} = \xi - \xi_{plastic} - \xi_{thermal} \qquad (3.19)$$

Solving equations (3.17), (3.18) and (3.19) we get

$$\{\boldsymbol{\sigma}\}=[D]\ \xi - \xi_{plastic} - \xi_{thermal} \qquad (3.20)$$

3.4.2 Theory of Welding Residual Stress

In welding process, during heating or cooling of metal, the metal will shrink and hence making actual prediction is difficult. During heating process, the temperature of the weld increases, the yield strength decrease, and the specific heat and coefficient of thermal expansion increase [16].

Welding stress during welding process on a plate is shown in the figure 3.8. Figure 3.8(a) gives the occurrence of plastic deformation during welding process. Figure 3.8(b) gives the temperature changes during welding and the distribution of stress is shown in figure 3.8(c).

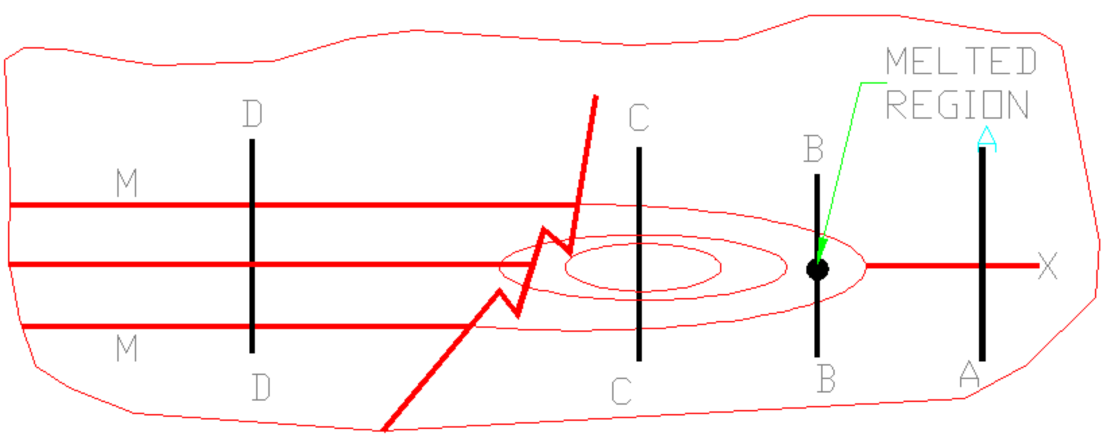

Figure 3.8(a) Weldment of large plate

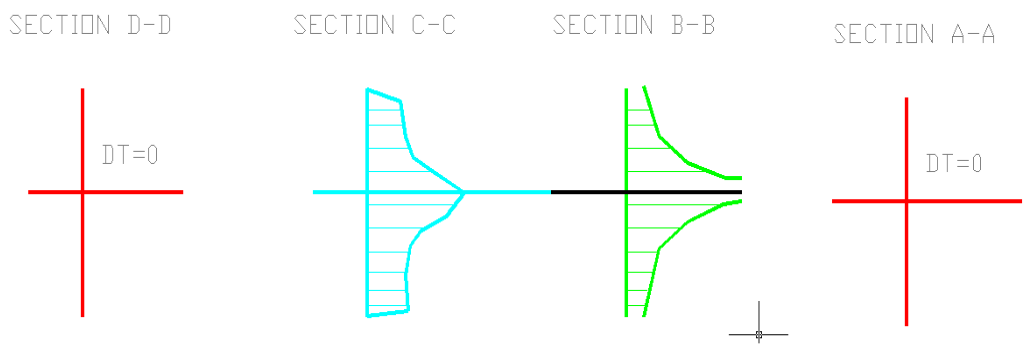

Figure 3.8(b) Temperature distribution during welding

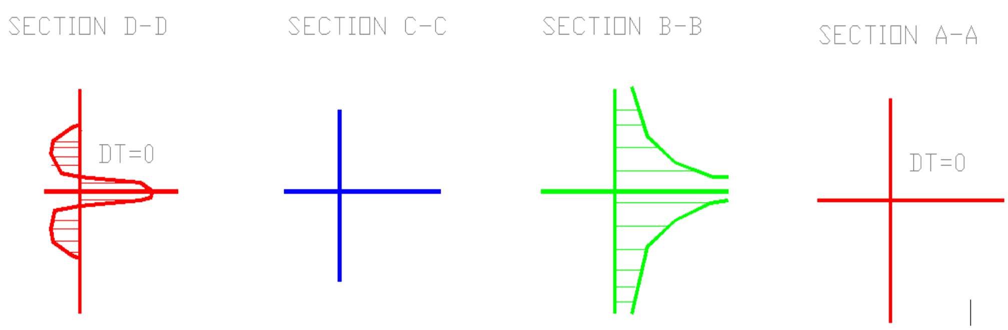

Figure 3.8(c) Distribution of stress during Welding

Figure 3.9 shows three different types of residual stress caused during distortion. Longitudinal and transverse shrinkage occur in plane distortion of the work piece. Plane or axi-symmetrical angular shrinkage occur perpendicular to the plane.

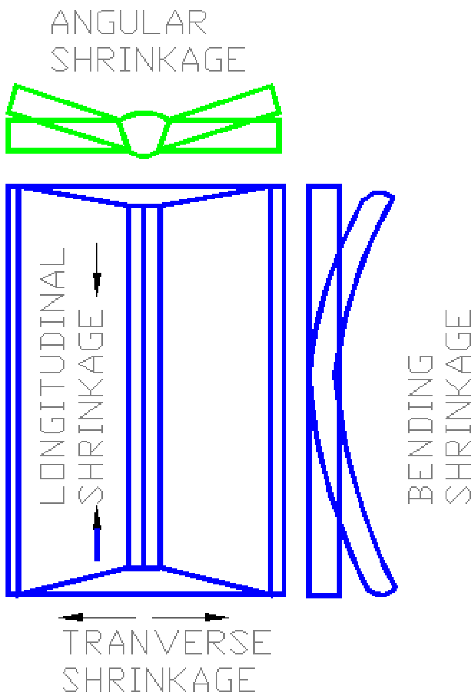

Figure 3.9: Example of distortion that can occur during welding

Figure 3.10 shows the deformation of a welded plate when a longitudinal edge is heated by a moving welding arc.The plate first deforms like the curve AB and the deformation increases and becomes as like ABCD.

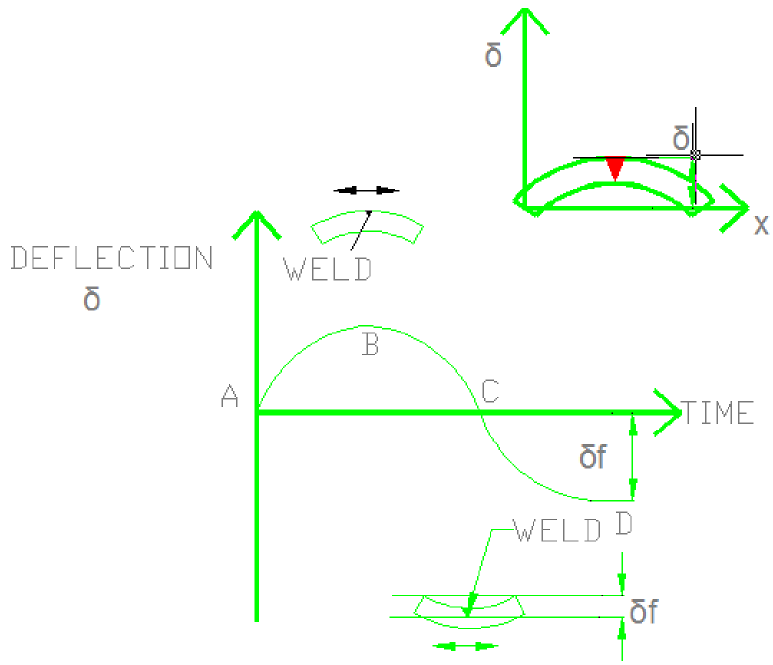

Figure 3.10 Deformation of Welded Plate under Influence of Moving Heat Source

3.5 Comparison of welded and riveted structures

Welded structures are superior in many respects to riveted structures. Welding has many advantages over other joining methods and is given below:

3.5.1 Advantages of welded structures

(a) Welded structure can achieve 100% Joint efficiency. Joint efficiency is defined as (Strength of a joint/strength of base plate) x100 (%) .

(b) For structures requiring water tightness, welded structure is more ideal than riveted structures.

(c) In welded structures, the weight can be reduced from 10 to 20%

(d) Welded plate does not have any limit on thickness.

(e) Welded structure has simple joint designs compared to riveted structures.

(f) Welded structure can be fabricated in a short time.

3.5.2 Disadvantages of welded structures

(a) If a crack starts in a welded structure, it is very difficult to arrest it.

(b) Welded structure has the possibility of defects such as porosity, cracks and slag.

(c) It is difficult to weld some materials such as Steel without cracks.

(d) Lack of reliable NDT technique.

(e) Local heating during welding cause thermal stresses and distortion.

3.6 Different welding processes

Some of the other types of welding process available are given below

1. Fusion welding
2. Electrical-resistance welding
3. Solid phase welding
4. Liquid – solid phase joining
5. Adhesive bonding.

3.7 Welding of Aluminum alloy structures

Aluminum is used in welding due to its low density. Aluminum alloys also have good fracture toughness at low temperatures.

3.8 Metallurgy and properties of aluminum alloys

Pure aluminum is used with other metals and produce different physical properties and mechanical properties. Table 3.1shows the major alloying elements of aluminum.

Table 3.1: Alloying elements of Aluminum

SL. NO.	Major alloying element
1	99.0% minimum Aluminum
2	Copper
3	Manganese
4	Silicon
5	Magnesium
6	Magnesium and silicon
7	Zinc

3.9 Welding of Stainless steel structures

Stainless steels has high corrosion resistance and high temperature oxidation resistance. Researchers identify various types of stainless steel components needed for welding process.

3.10 Metallurgy and properties of Stainless steel

The properties of the stainless steels are obtained by adding elements such as chromium and nickel, to steel. The alloying elements of stainless steel are shown in Table 3.2.

Table 3.2 Micro Structure of elements of Stainless steel

SL. NO.	Major alloying element
1	Austenitic
2	Ferritic
3	Martensitic
4	Duplex

The first three groups consist of a single phase and the fourth group contains both ferrite and austenite in the microstructure.

3.11 Comparison of mechanical properties of Aluminum alloy and stainless steel

- Weight of Aluminum is less than half of the steel for the same strength.
- Aluminum is less notch sensitive than many steels.
- Aluminum is ductile even at low temperatures.

3.12 Major problems in Aluminum welding

- Aluminum alloys are more active than steel and will subject to weld porosity.
- Aluminum has higher heat conductivity and subject to weld with more shrinkage.
- In heat treated alloys a reduction of strength is noticed in weldment in aluminum.

CHAPTER FOUR: MODELING AND ANALYSIS

4.1 Modeling of Heat Source

Welding variables such as current, arc length takes an important role in weld shape. Goldak [34], [35], [36], proposed a three-dimensional double ellipsoidal heat flux model to note stress and strain fields. Goldak double ellipsoidal heat source model is shown in figure4.1.

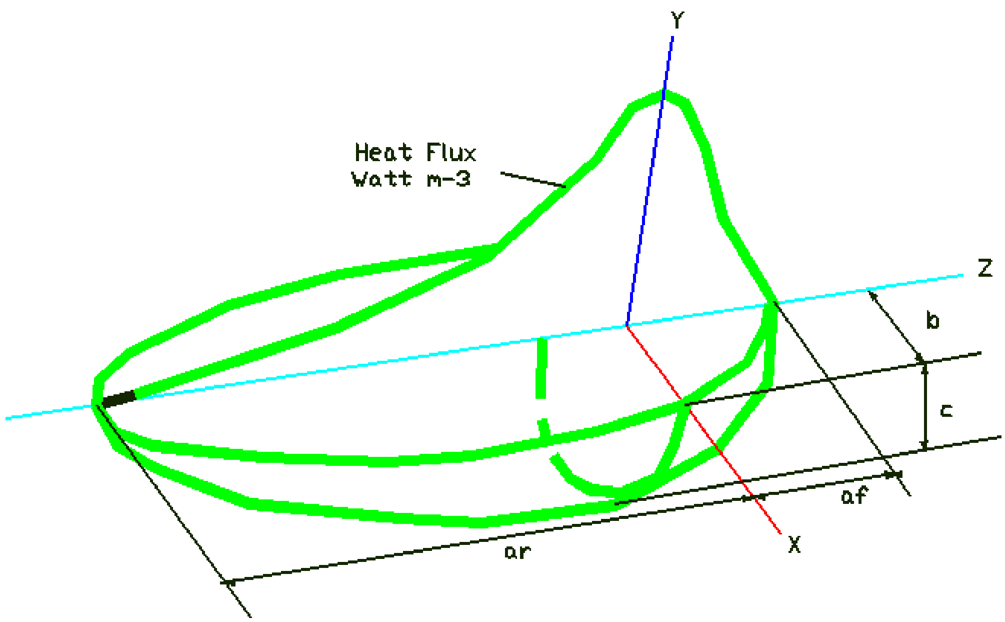

Figure 4.1 Goldak double ellipsoidal heat source model

The power density distribution of the front half is shown in equation (4.1)

$$q(x,y,z) = \frac{6 .\sqrt{3} .Q\ \eta f_f}{a_f .b .c .\pi .\sqrt{\pi}} . e^{(\frac{-3x^2}{b^2} - \frac{3y^2}{c^2} - \frac{3z^2}{a_f^2})} \qquad (4.1)$$

The power density distribution of the rear half is shown in equation (4.2)

$$q(x,y,z) = \frac{6.\sqrt{3}.Q\ \eta f_r}{a_r.b\ .c\ .\pi\ .\sqrt{\pi}} .\ e^{(\frac{-3x^2}{b^2} - \frac{3y^2}{c^2} - \frac{3z^2}{a_r^2})} \quad (4.2)$$

Where Q=VI

V= Input Voltage, I= Input Current, η=Efficiency, and v = Welding speed,

a, b, c are the semi axes of the ellipsoid in the directions x, y and z.

$c_f$is the semi axes of the ellipsoid in +Z directions

c_b is the semi axes of the ellipsoid in -Z directions

The Modified double ellipsoid model for circumferential welding for front and rear half is shown in equations (4.3) and (4.4)

$$q_f = \frac{6.\sqrt{3}.Q.M(r,z)f_f}{a_r.b\ .c\ .\pi\ .\sqrt{\pi}} .\ e^{-3(\frac{r^2\theta^2}{a_r^2} + \frac{3z^2}{b^2} + \frac{R_0^2 + r^2 - 2rR_0}{c^2})} \quad (4.3)$$

$$q_r = \frac{6.\sqrt{3}.Q.M(r,z)f_r}{a_r.b\ .c\ .\pi\ .\sqrt{\pi}} .\ e^{-3(\frac{r^2\theta^2}{a_r^2} + \frac{3z^2}{b^2} + \frac{R_0^2 + r^2 - 2rR_0}{c^2})} \quad (4.4)$$

4.2 APDL

APDL stands for ANSYS Parametric Design Language. APDL is a scripting language and is used to automate tasks using parameters. APDL also has other commands such as if loop, if then else, do loop, scalar, vector and matrix operations.

4.3 Communicating via Commands

ANSYS is programmed by the use of commands. Each command has a specific function and ANSYS has more than 1300 commands. All commands are associated with a processor. Some commands have one or more processors. Frequently used commands can be recorded in command file. Command file is also known as macro file. In this thesis ANSYS macro was developed for simulating the welding process.

4.4 Model description

In this thesis, a pipe of dimensions, 150 mm length, 100mm diameter and 4.5mm thickness is taken for analysis modeled with two different materials (aluminum and steel properties). On the left corner of the pipe a bead is deposited over the entire diameter. The model is generated by means of direct node generation. The heat transfer analysis requires thermal conductivity, specific heat, density and combined convection and radiation heat coefficient. For elasto plastic analysis the modulus of elasticity, yield strength, Poisson ratio, and thermal expansion coefficient are required.

Material properties of AA7020 and SI304 are plotted in figure 4.2 and 4.3

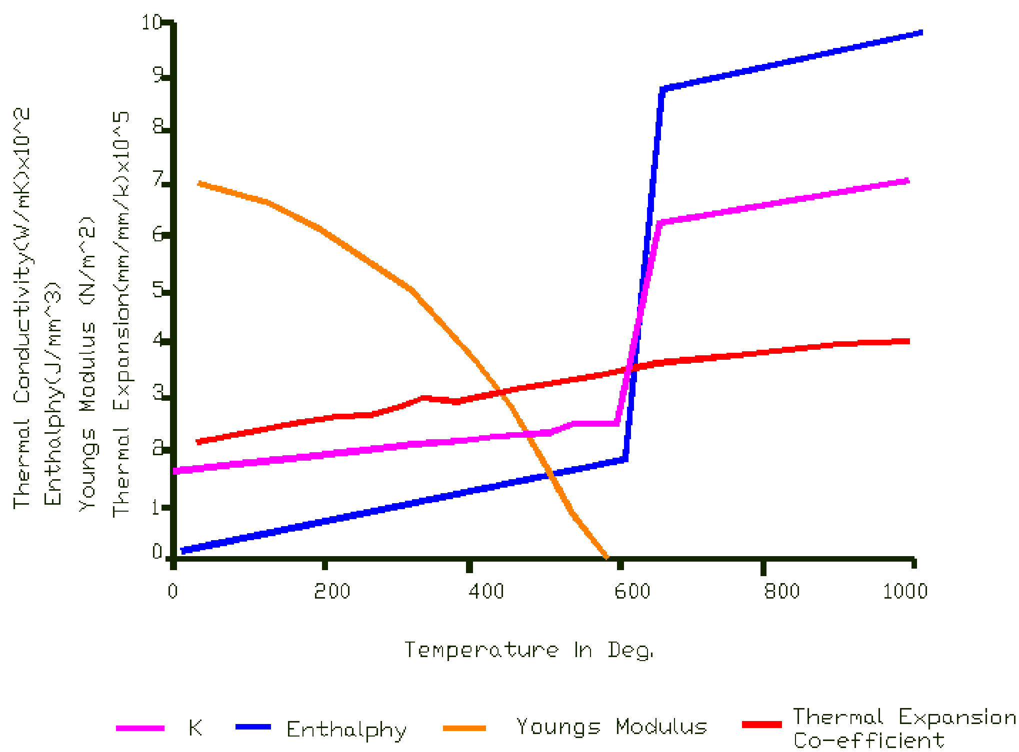

Figure 4.2 Temperature Dependent Material properties for AA7020 alloy

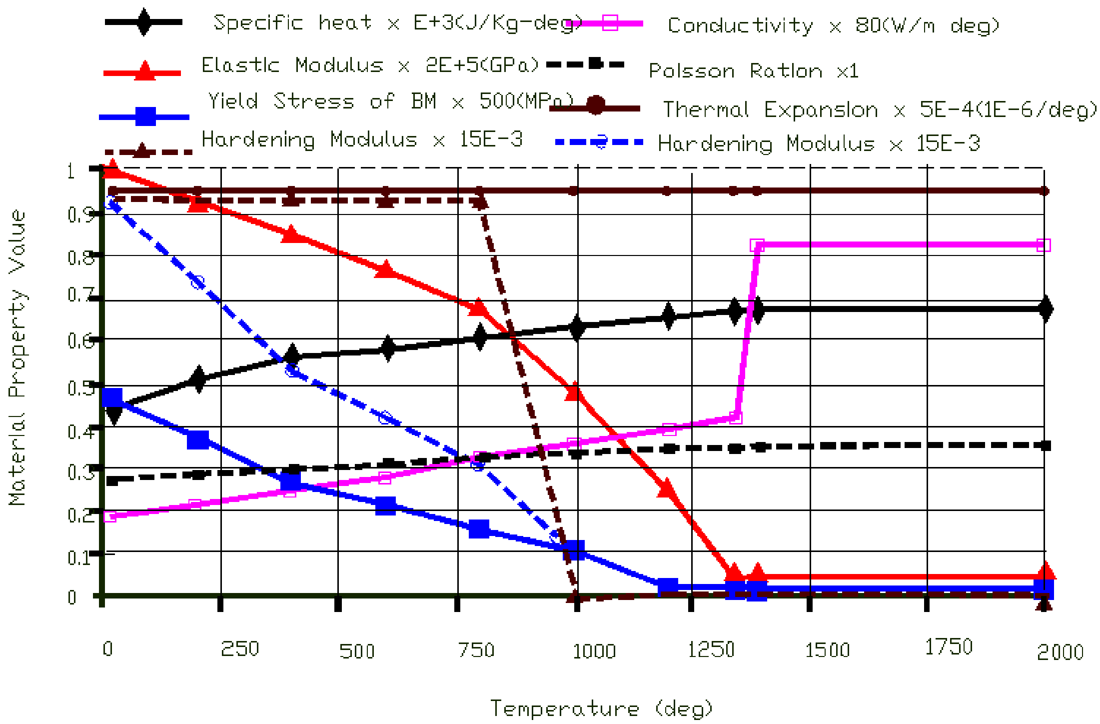

Figure 4.3 Material properties of AISI- 304 Stainless steel

4.5 Model assumptions

The following assumptions are made for heat transfer analysis

- All boundaries except the top and side surface were assumed to satisfy the adiabatic condition.
- The portion underneath the arc was assumed to be insulated during the time the arc was applied to the surface.
- A combined convection and radiation boundary condition was used on the remaining of the top surface. The formula is as follows:

$H = 24.1 \text{ X } 10^{-4} \xi T^{1.61}$

Where, H is the combined convection and radiation heat transfer

Coefficient ξ is thermal emissivity, and T is the temperature.

- The analysis is based on quasi-steady state, i.e., the heat source is moving at a constant velocity.

- ➢ Effective depth of penetration is shallow, thus, Gaussian heat flux distribution was used on Heat Affected Zone (HAZ).

4.6 SOLID70

SOLID70 has three-dimensional thermal conduction capability. The 3D thermal solid structure is shown in figure 4.4. SOLID70 element has eight nodes. This element is used in steady-state, three-dimensional or thermal analysis.

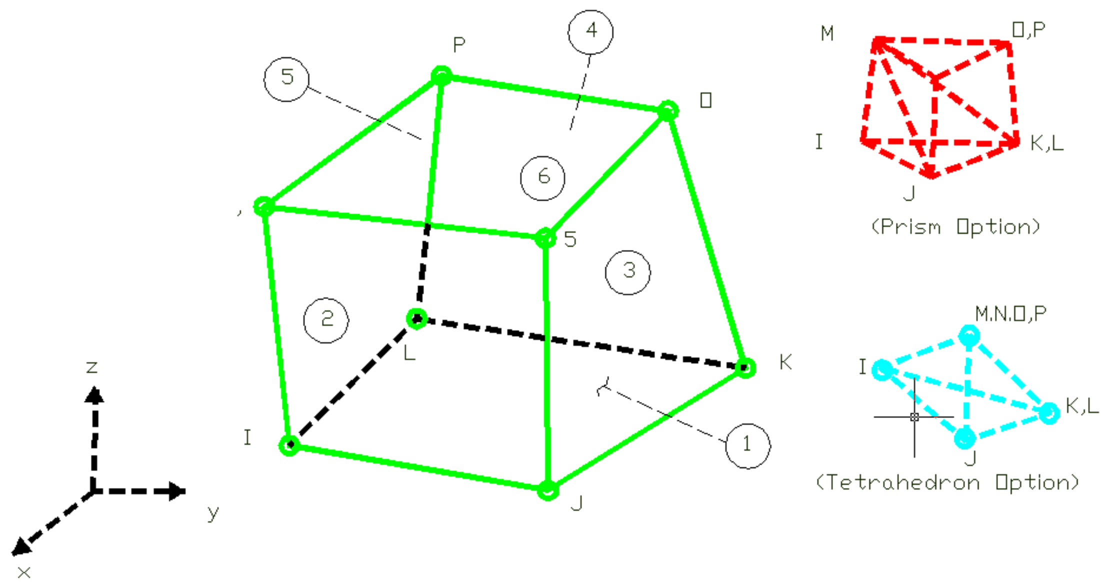

Figure 4.4SOLID70 3-D Thermal Solid

From the figure 4.4 it can be noticed that the major nodes of the element SOLID70 is I, J, K, L, M, N, O and P. The real constants are VX, VY and VZ. The real constants are the inputs for the element coordinate system. For stable operation, temperature should be specified throughout the entire boundary.

4.7 SOLSH190

SOLSH190 is a three dimensional structure. It has 8 nodes. SOLSH190 is used or simulating thin to moderately thick shell structures.3 Dimensional thermal solid structure of SOLSH190 is shown in figure 4.5.

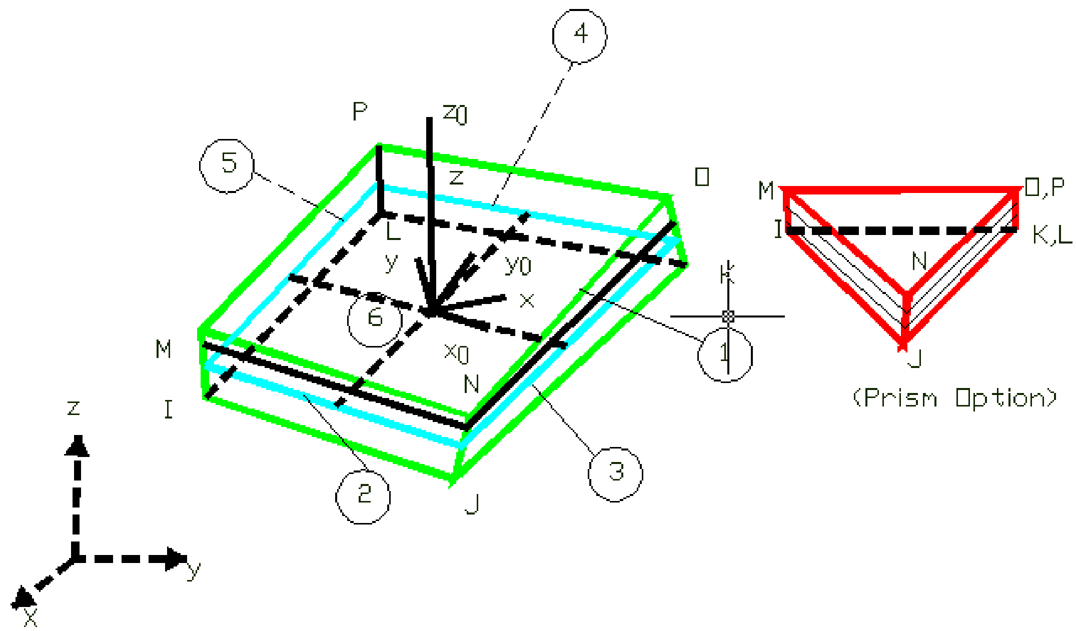

Figure 4.5SOLSH190 3-D structure

From the figure 4.5 it can be noticed that the major nodes of the element SOLSH190 is I, J, K, L, M, N, O and P. The degree of freedom is UX, UY and UZ. SOLSH190 does not have any of the real constants.

4.8 Thermal structural analysis

Thermal structural analysis is done using the Modified Double Ellipsoidal equation and is shown in equation (4.5)

$$Q_{eff} = \frac{24 .Q .r_{(f,b)} .\sqrt{3} .e^{\left(\frac{-3 .x^2}{a^2} - \frac{3 .y^2}{b^2} - \frac{3 .z^2}{c^2}\right)}}{\pi .\sqrt{\pi} .a .b .c .E(w ,a) .E(t ,b) .E(1 ,c)} \quad (4.5)$$

Where a, b, c is the region of heat flux

$$Q = \eta VI \tag{4.6}$$

(Where η, V, and I are arc efficiency, arc voltage, and arc current)

The result of heat transfer is time dependent and is modeled using convection and radiation heat transfer. Also, it is to be assumed that the convective coefficient vary with temperature.

4.9 Bilinear Kinematic Hardening

Bilinear Kinematic Hardening is used for materials that obey von Misses yield criteria. The material considers the initial slope of the curve as the elastic modulus of the material. This slope continues till particular yield stress. After that, the curve continues along the second slope. The second slope is defined by tangent modulus. Tangent modulus have the same units as the elastic modulus. The tangent modulus is not zero or greater than the elastic modulus. Thus kinematic hardening effect is brought into the model.

4.10 Material Addition

Material addition is needed in order to study the penetration effects on the material during welding process. Material addition is achieved by means of a feature called as birth and death feature. This birth and death feature is available in ANSYS.

4.10.1 Birth and Death Feature

The material addition is achieved by using birth and deathfeature. Figure 4.6 shows the model for material addition. Death feature is achieved by the ANSYS code. At first, the weld elements are deactivated. This deactivation is done by using a huge reduction factor. Meanwhile, to obtain the birth element effect, death element is reactivated again.

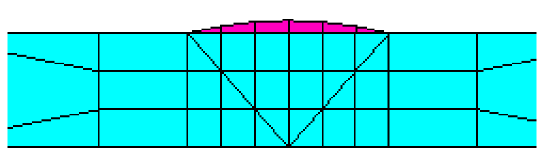

Figure 4.6 Model for Material Addition

CHAPTER FIVE: RESULTS AND DISCUSSION

5.1 Finite Element Analysis Procedure

Finite element model of pipe is shown in figure 5.1. and 5.2.

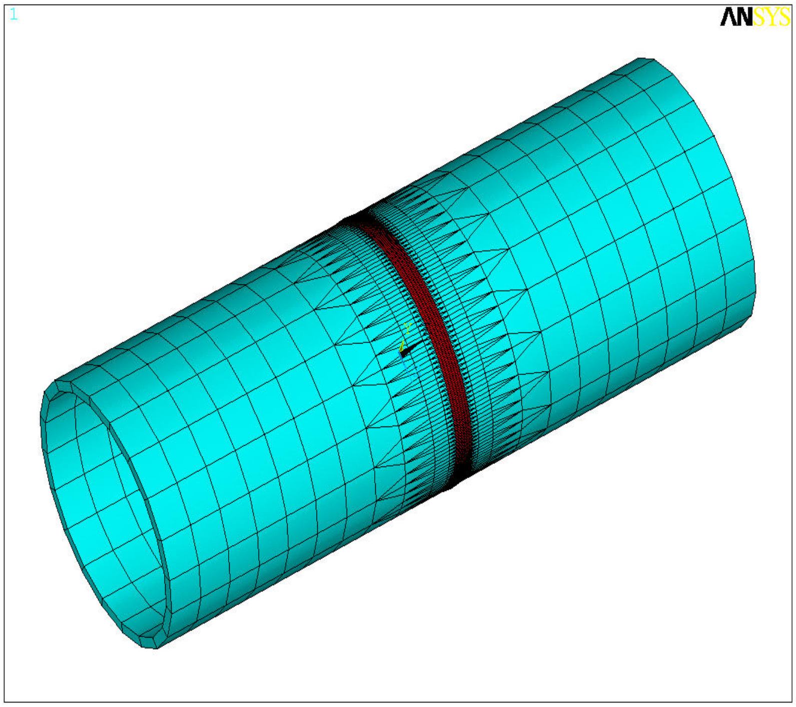

Figure 5.1 Solid Model of pipe

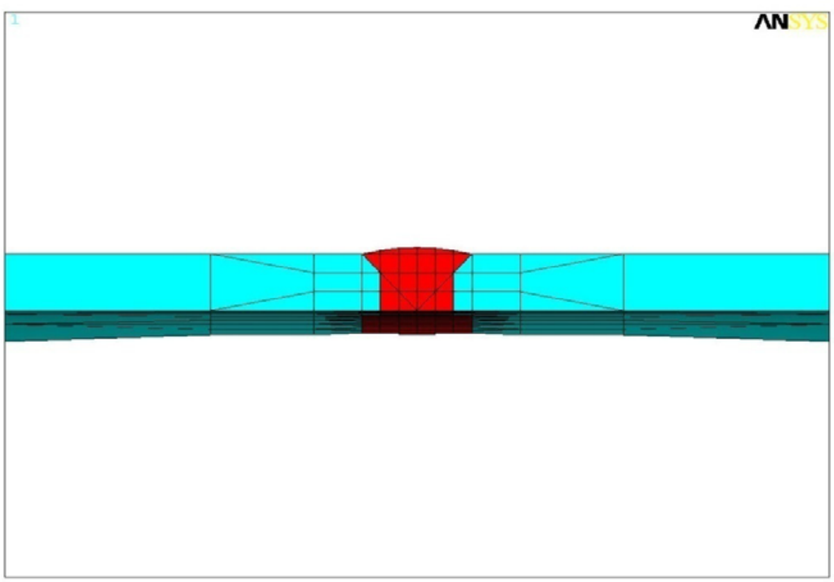

Figure 5.2 Solid Model- Cross section

Detail modeling and solving procedure is shown in the flow chart 5.3.

1) By using Solid70 pipe was modeled in ANSYS as structural and thermal model.
2) After modeling the pipe it was meshed as element in FEA
3) It was modeled based on local co-ordinate system (X_o,Y_o,$Z_{o)-}$
   X-direction denotes pipe width, Y-direction denotes pipe thickness and Z-direction denotes pipe length
4) This local co-ordinate was placed on the weld starting point.
5) Based on the local co-ordinate the heat load was applied in FEA
6) While analysis this local co-ordinate was moving on the weld boundary around pipe
7) Welding was done with respect to time similar to TIG welding processing.
8) After welding around the pipe the cooling was taken place at the time interval due to convection process.
9) This result was used for the post process.
10) After getting the temperature distribution of weld on pipe structural analysis of deformation, residual stress formation was plot by analysis.

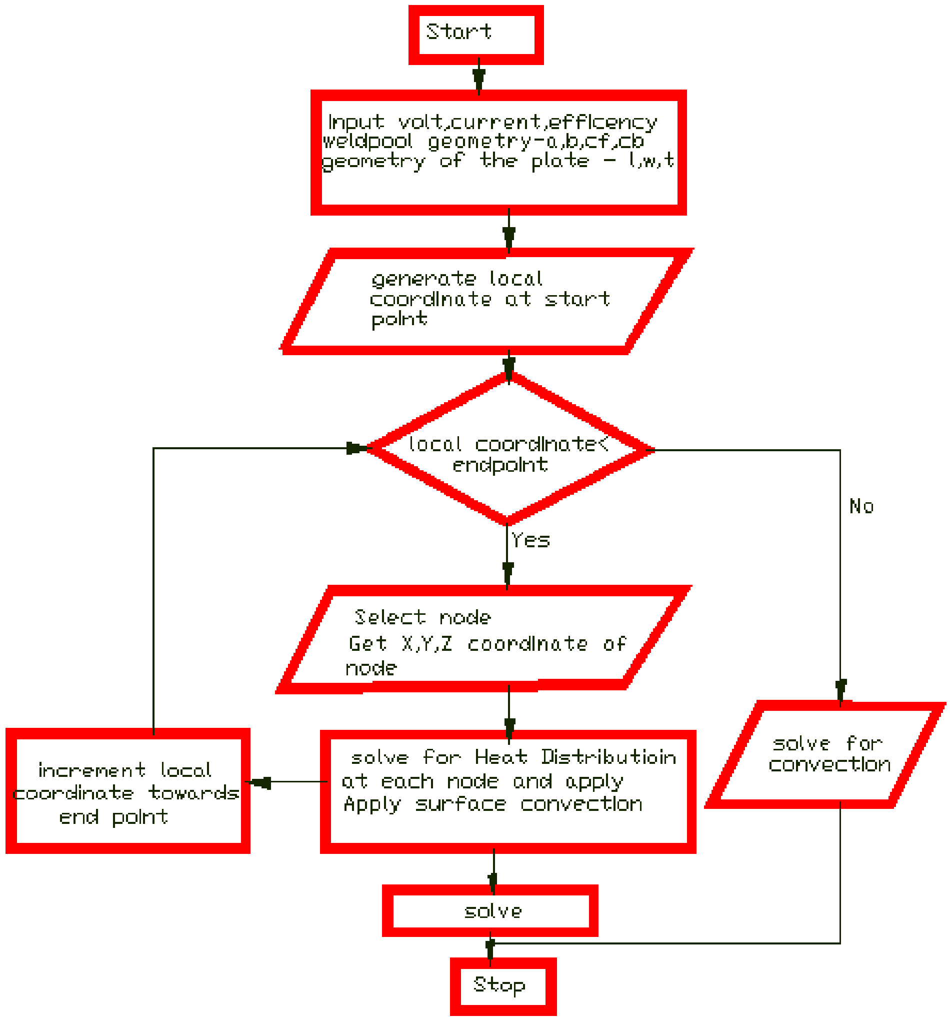

Figure 5.3 Flow chart diagrams for the solving procedure

5.2 Heat flow simulation

The heat source in this analysis is considered as Modified Double ellipsoidal equation. By using the above FEM procedure, temperature distribution at various times has obtained.

5.2.1 Results of Aluminum material

Figure 5.4-5.8 shows the variation of temperature at different time intervals. It is seen that the minimum base pipe temperature is about 108^{o}C at the end of the welding, which is then cooled down only by means of convection.

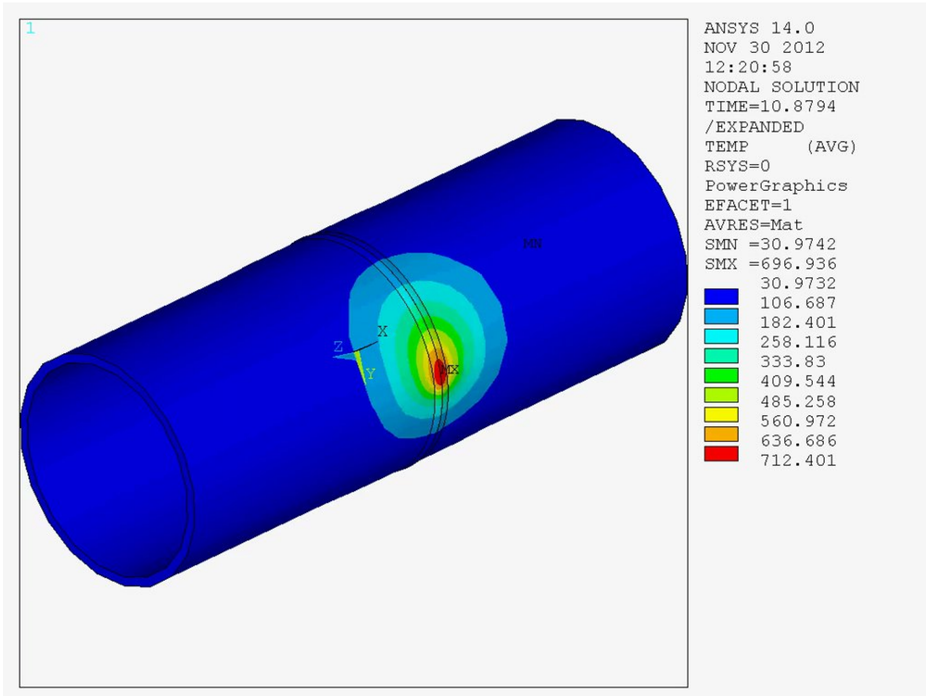

Figure 5.4 Temperature distribution (time=10 sec)

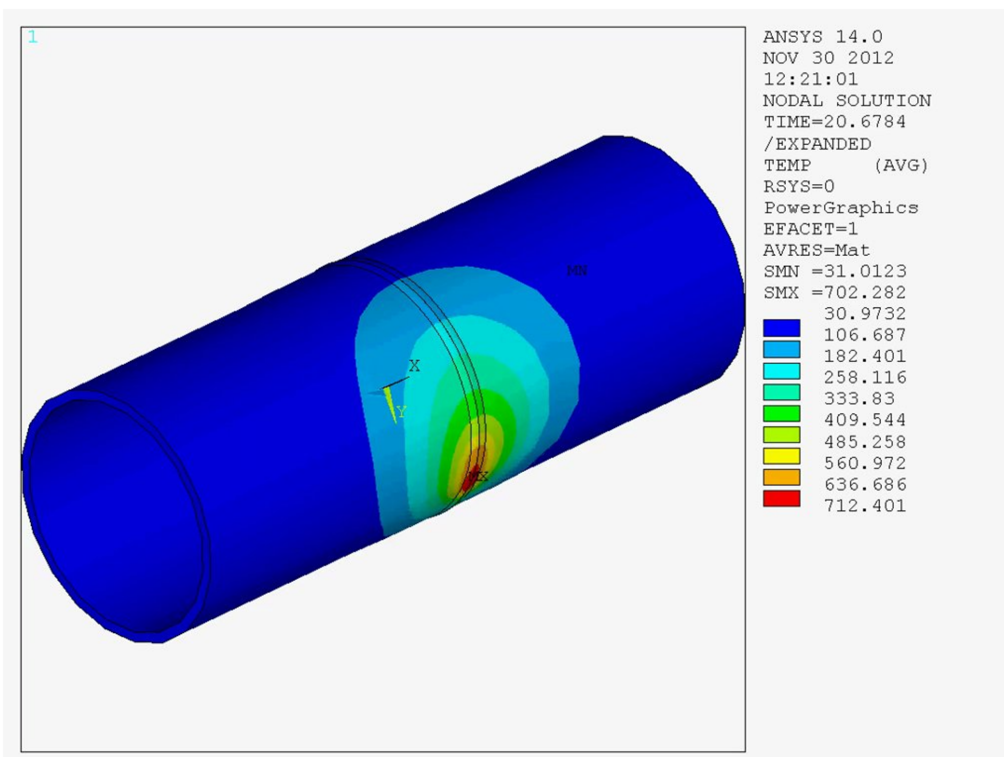

Figure 5.5 Temperature distribution (time=20 sec)

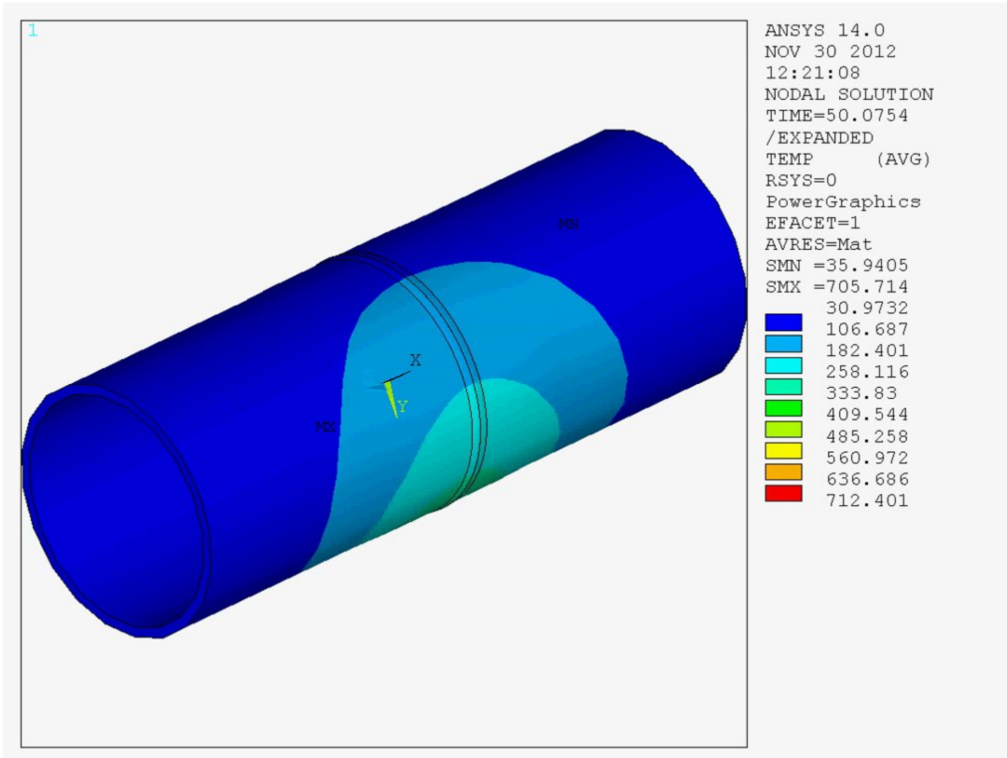

Figure 5.6 Temperature distribution (time=50 sec)

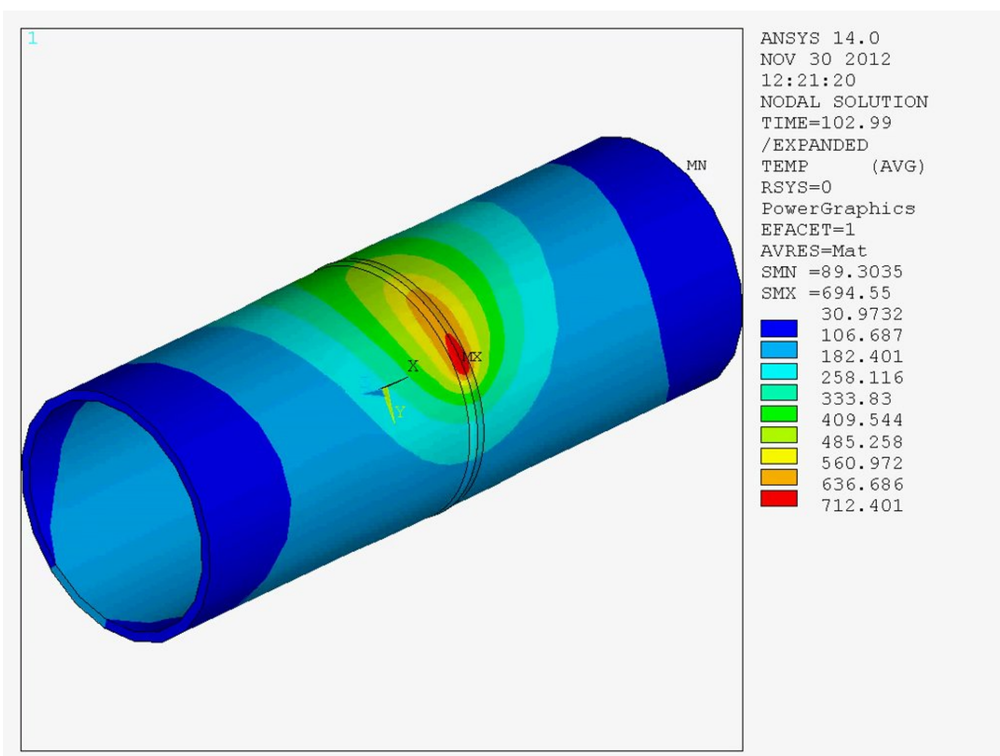

Figure 5.7 Temperature distribution (time=102 sec)

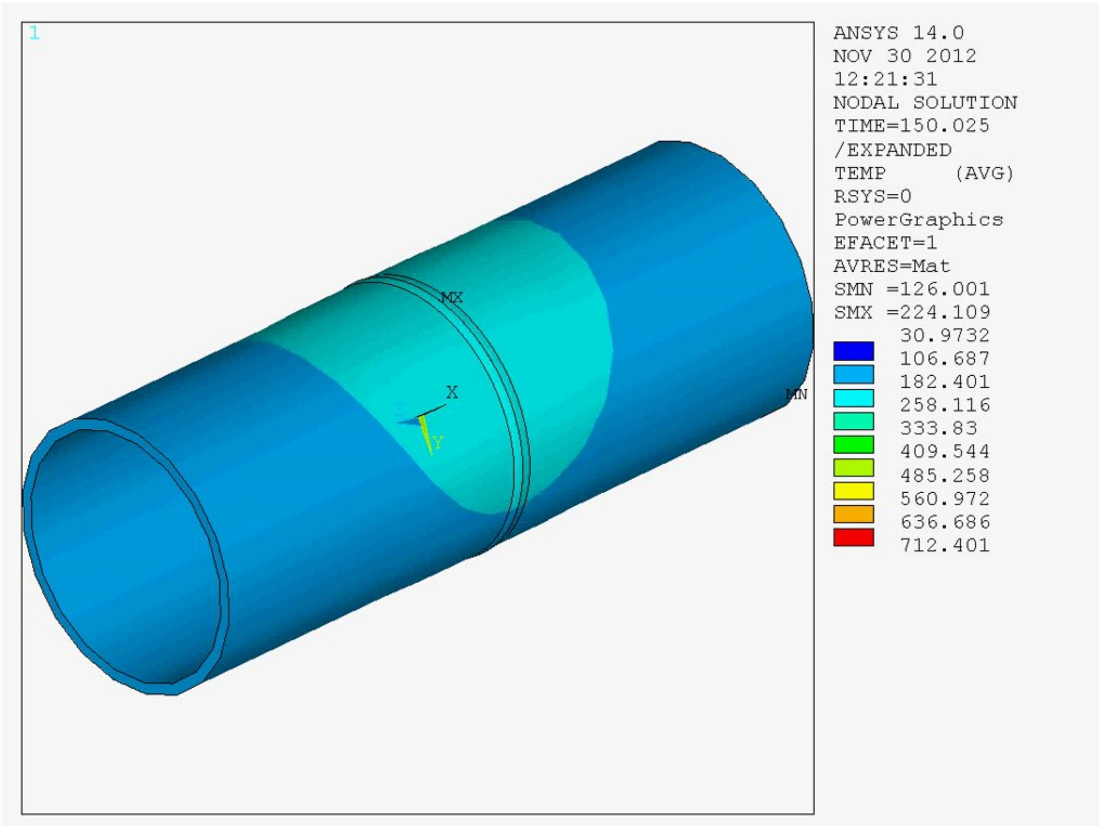

Figure 5.8 Temperature distribution (time=150 sec)

The time history is a significant record as it gives the heating and cooling rate that may prevail in welding. Such data is vital in obtaining data like residual stress, distortion, microstructure etc. .

Figure 5.09 to figure 5.19 **gives mechanical analysis results**.

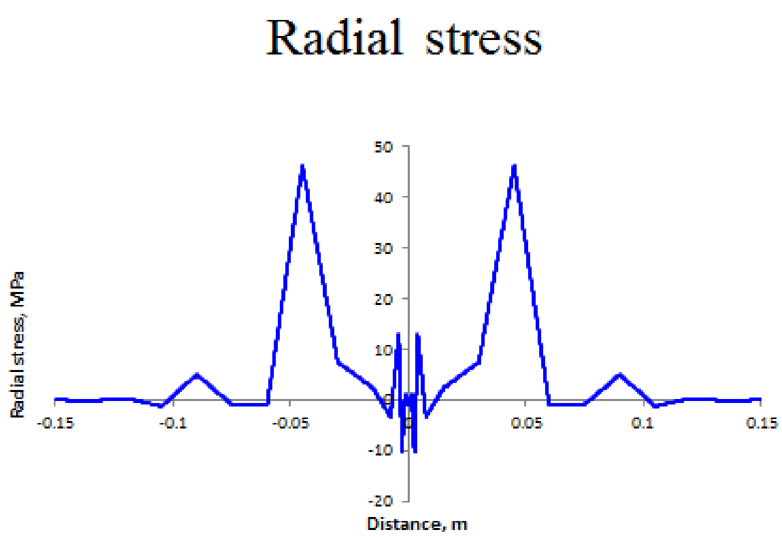

Figure 5.9 Radial stress plot

From the above figure, Radial stress is high near the butt weld joint and gradually decreased to the direction opposite to butt weld joint

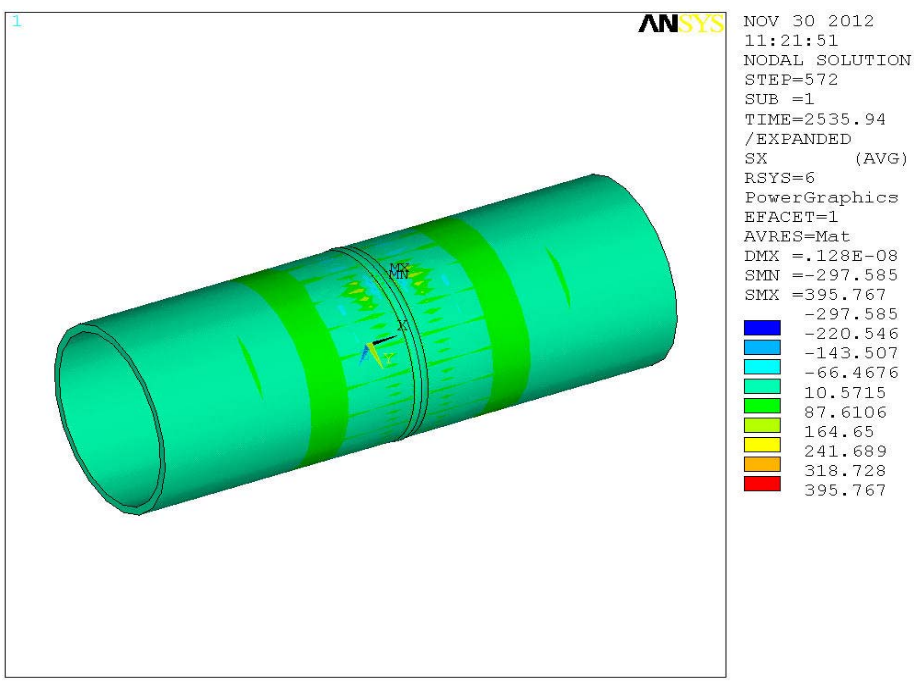

Figure 5.10 Radial stress - Contour plot

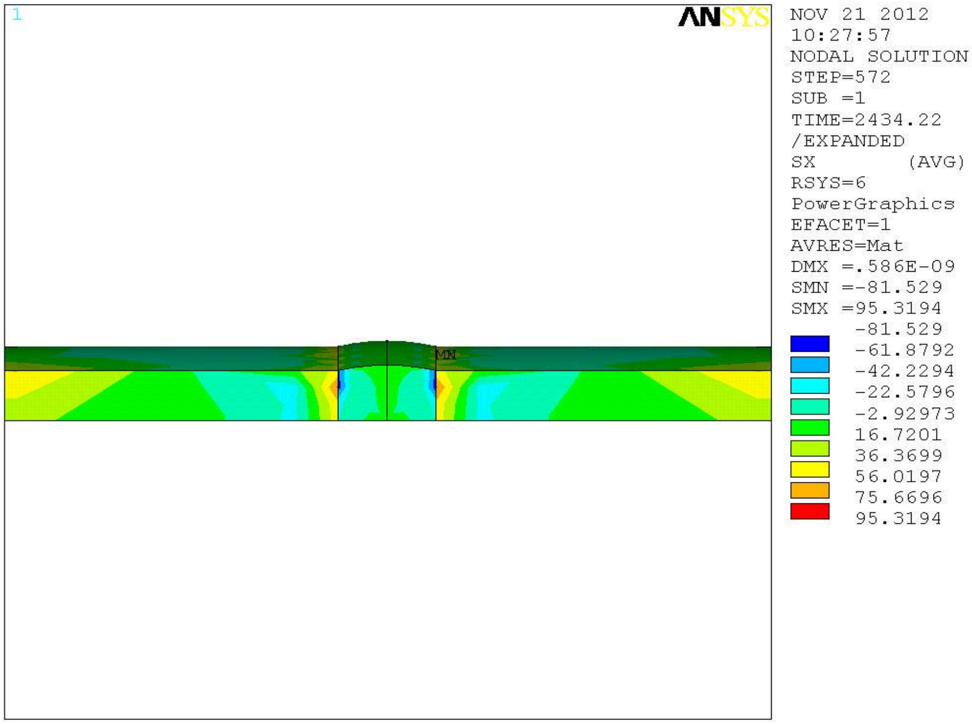

Figure 5.11 Radial stress - Contour plot Sectional view

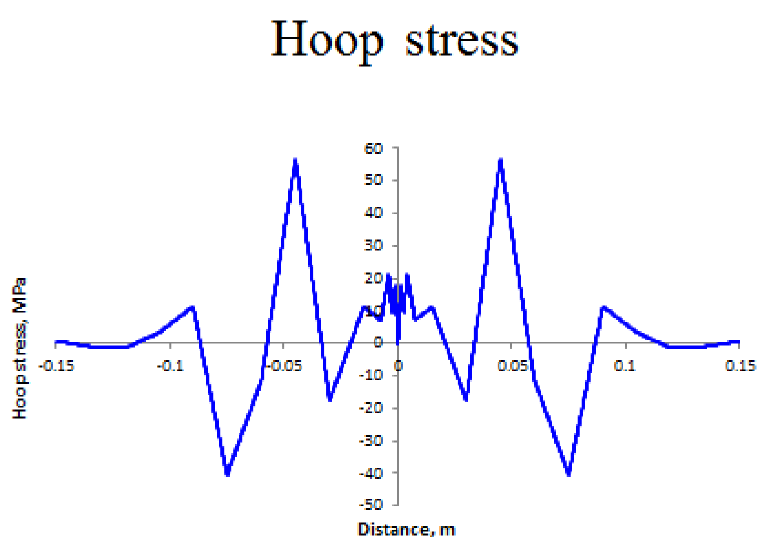

Figure 5.12 Hoop stress

From the above figure, Hoop stress is high near the butt weld joint and gradually decreased to the direction opposite to butt weld joint

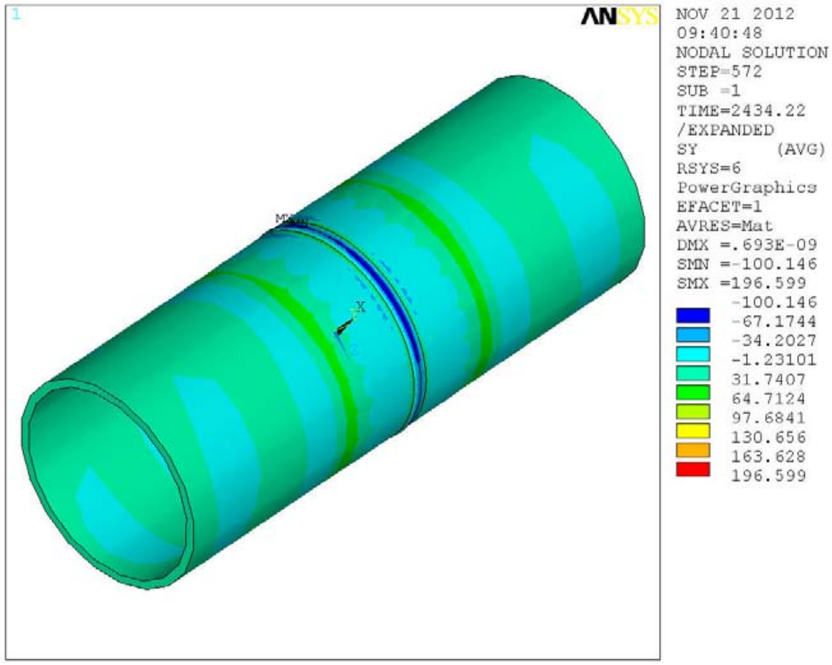

Figure 5.13 Hoop stress – Contour plot

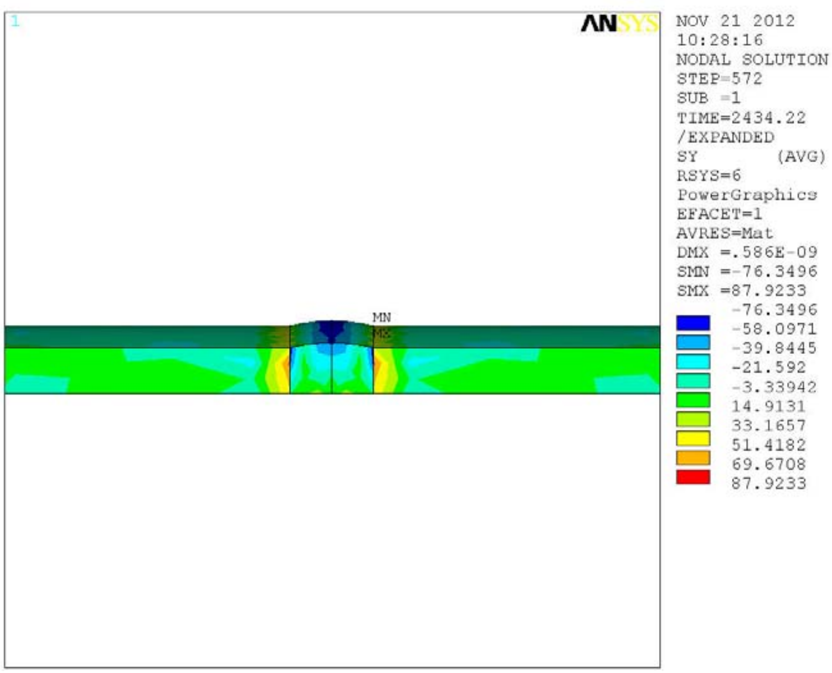

Figure 5.14 Hoop stress – Contour plot Cross sectional view

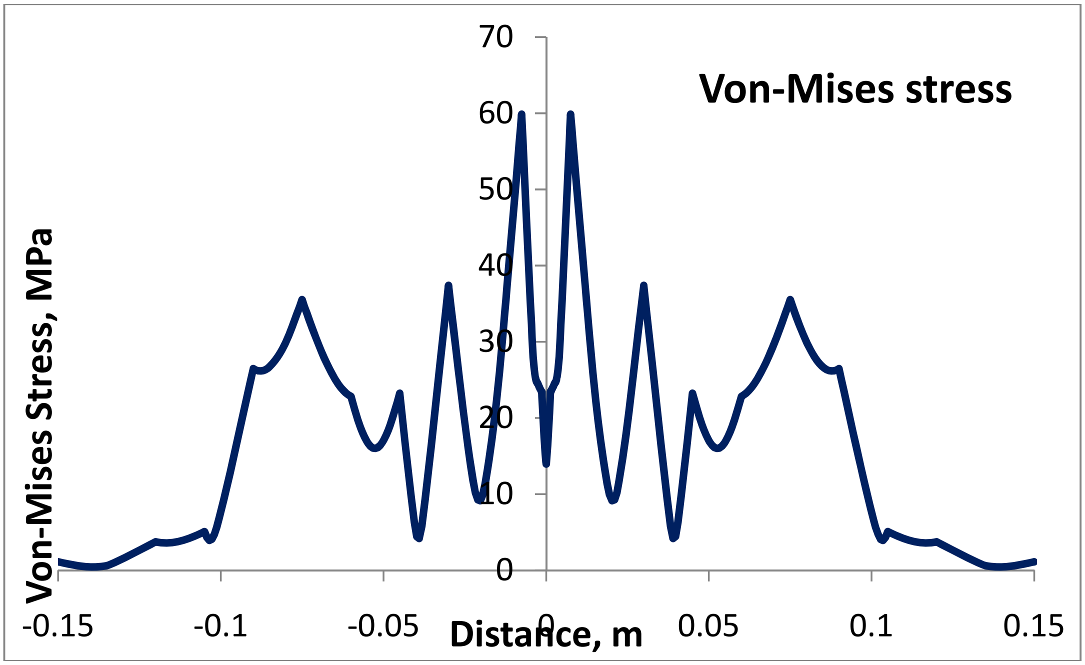

Figure 5.15 Von Mises stress

From the above figure, Von Mises stress is high near the butt weld joint and gradually decreased to the direction opposite to butt weld joint

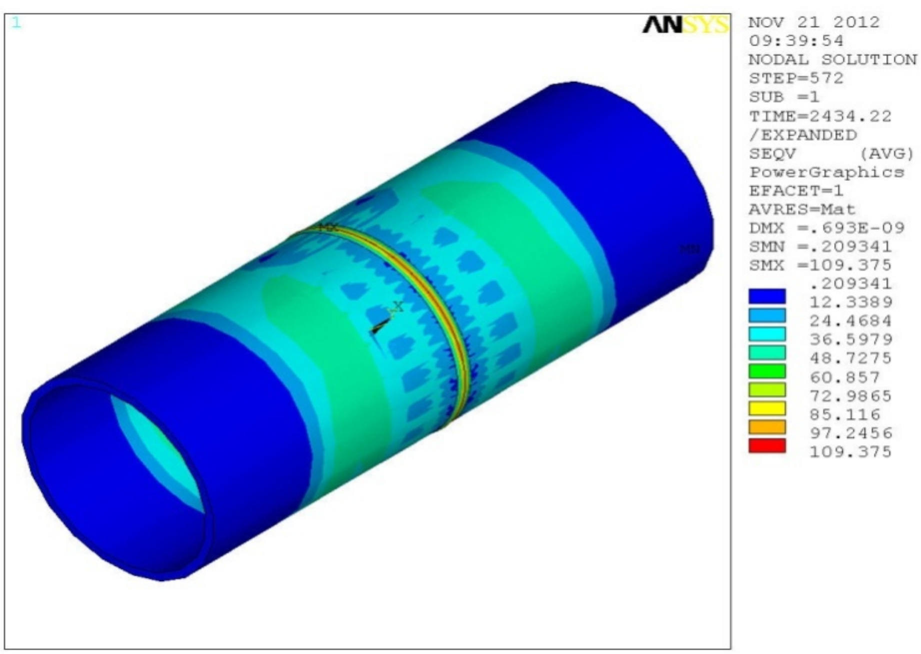

Figure 5.16 Von Mises stress – Contour plot

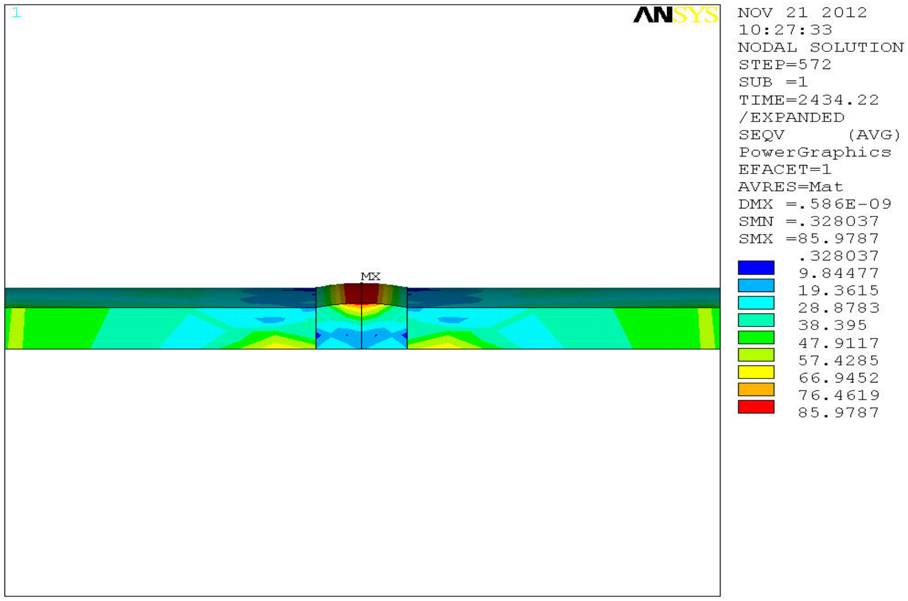

Figure 5.17 Von Mises stress – Contour plot Cross sectional view

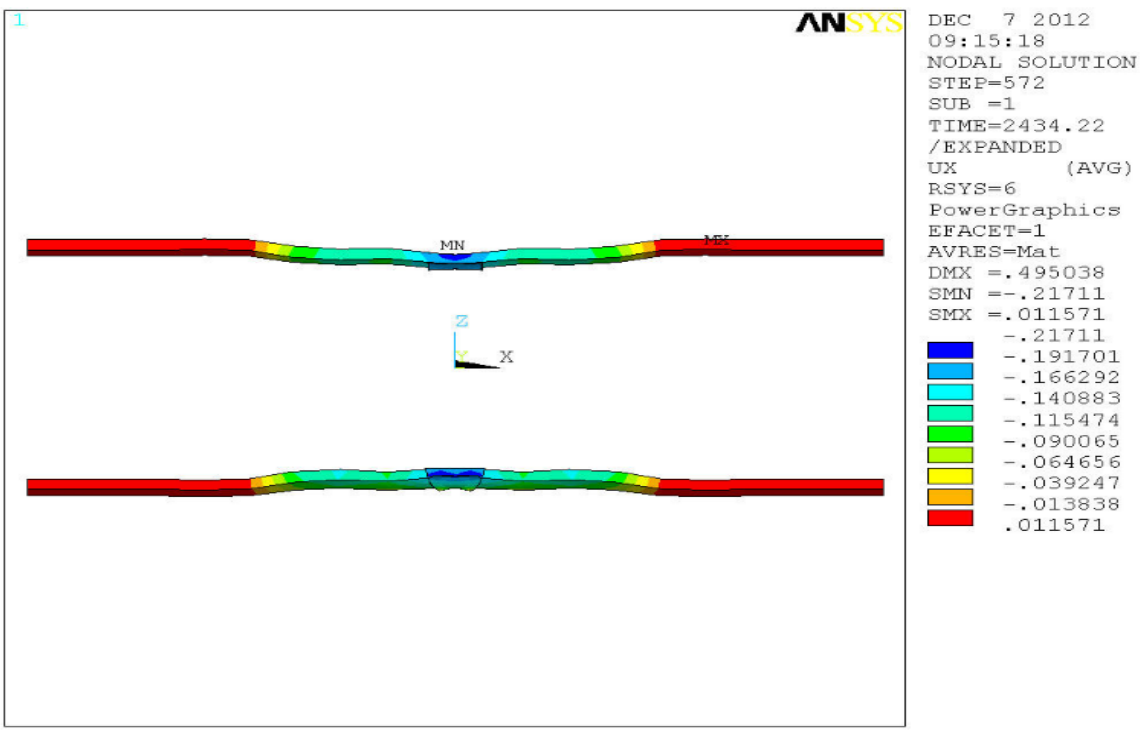

Figure 5.18 Deformation on Radial Direction.

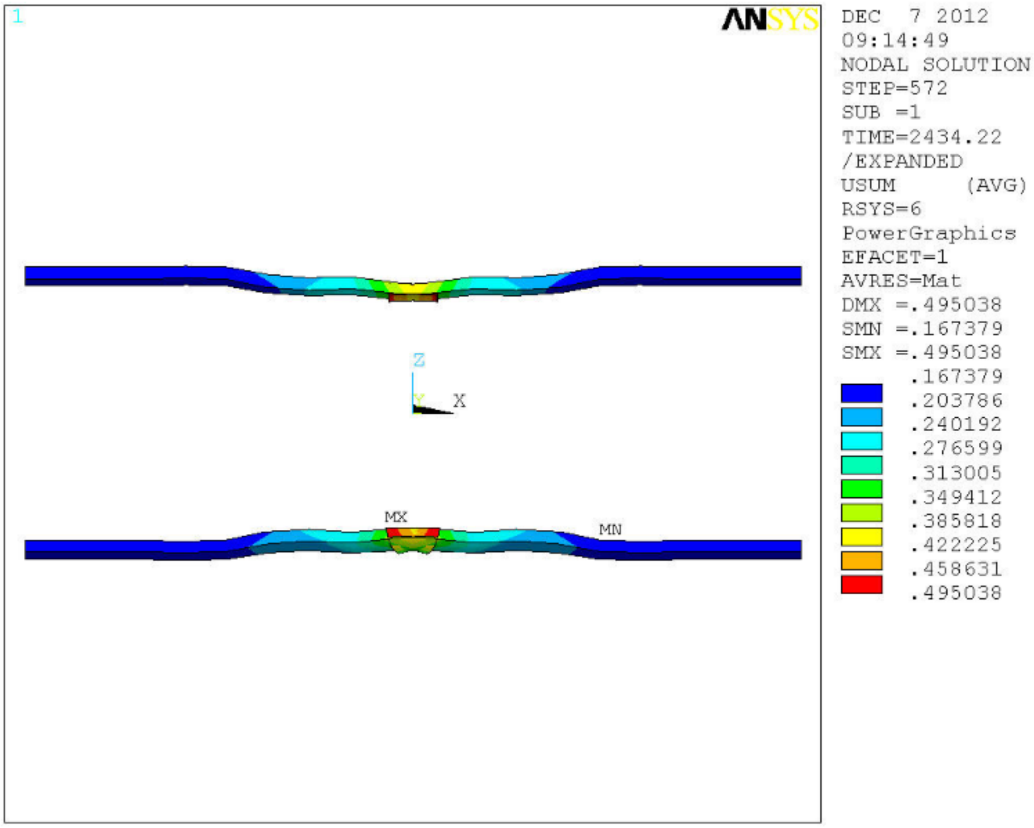

Figure 5.19 AbsoluteDeformation.

5.2.2 Results of Stainless Steel Material

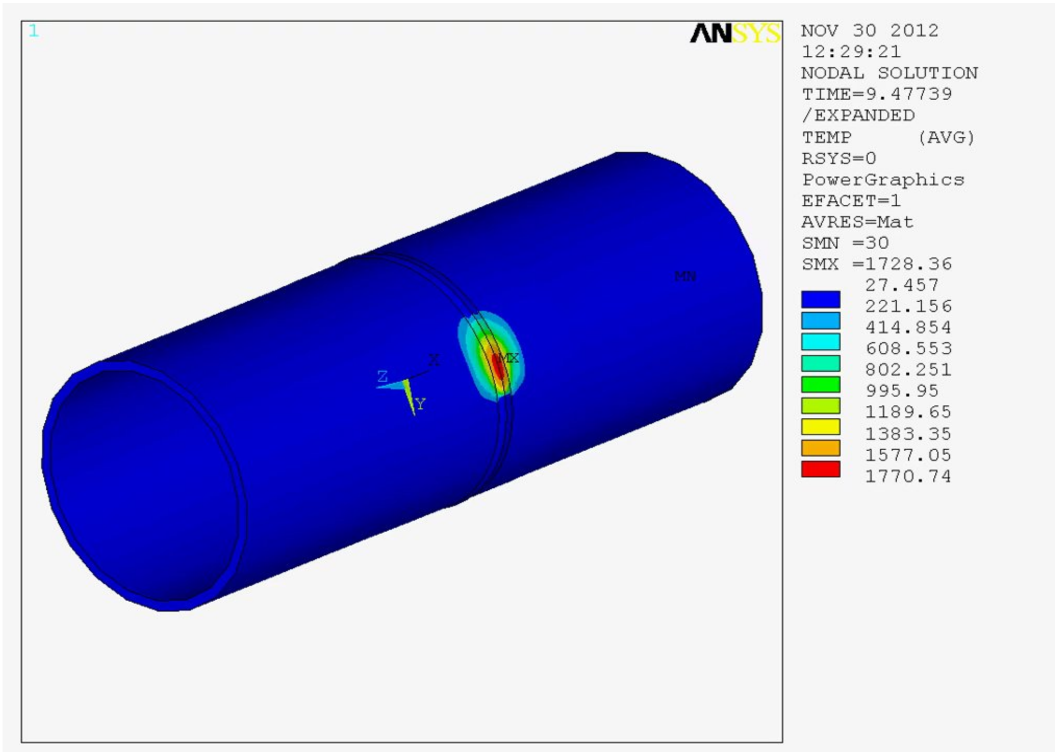

Figure 5.20 Temperature distribution (time=10 sec)

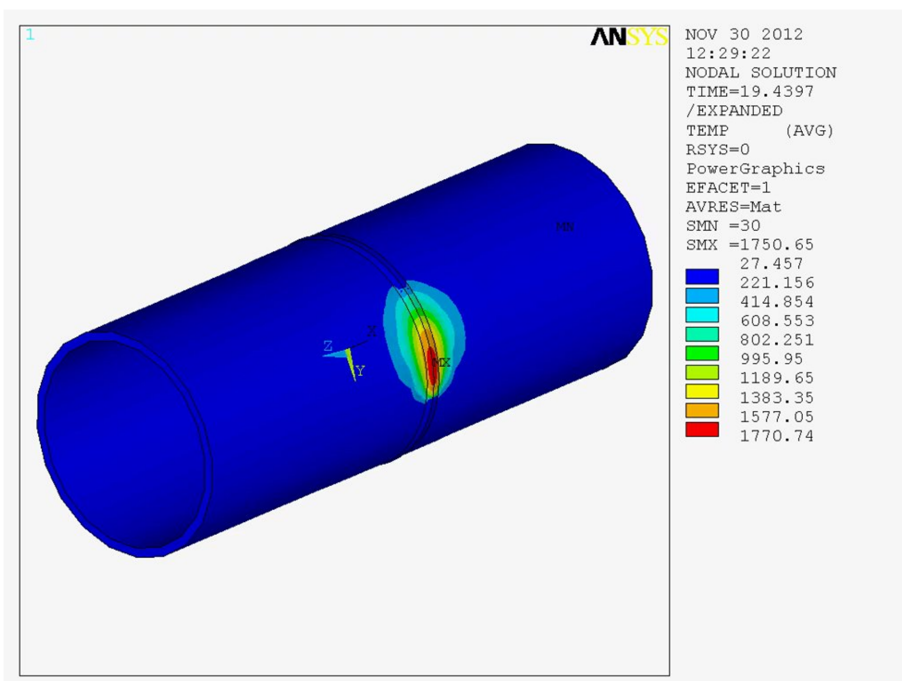

Figure 5.21 Temperature distribution (time=20 sec)

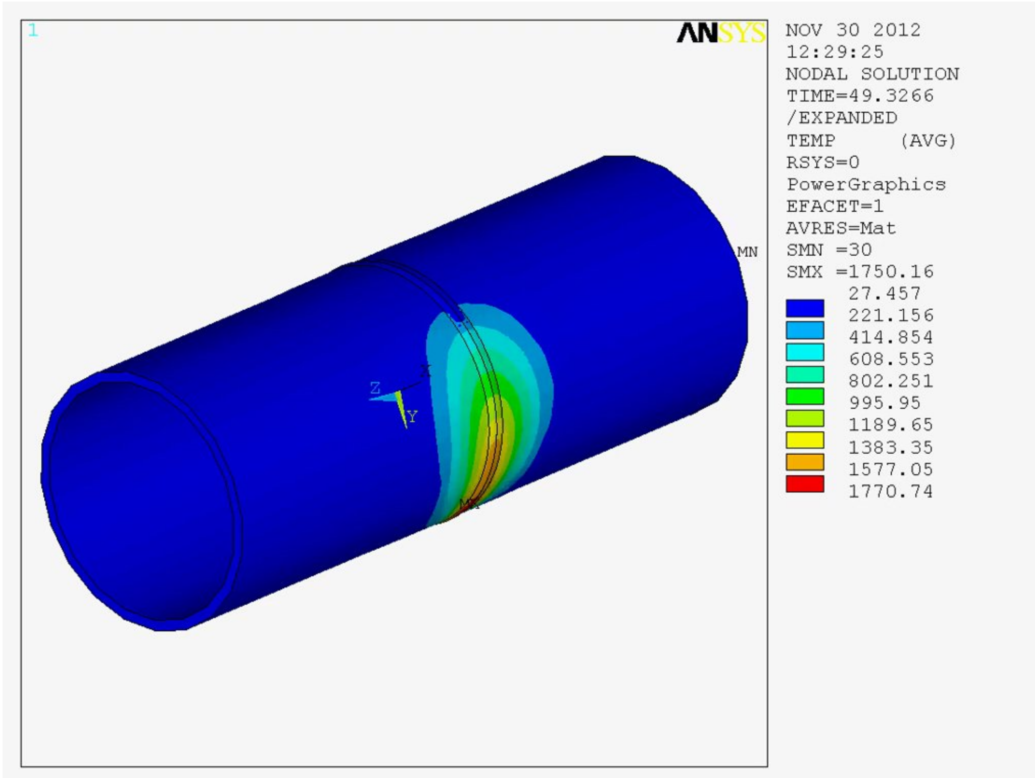

Figure 5.22 Temperature distribution (time=50 sec)

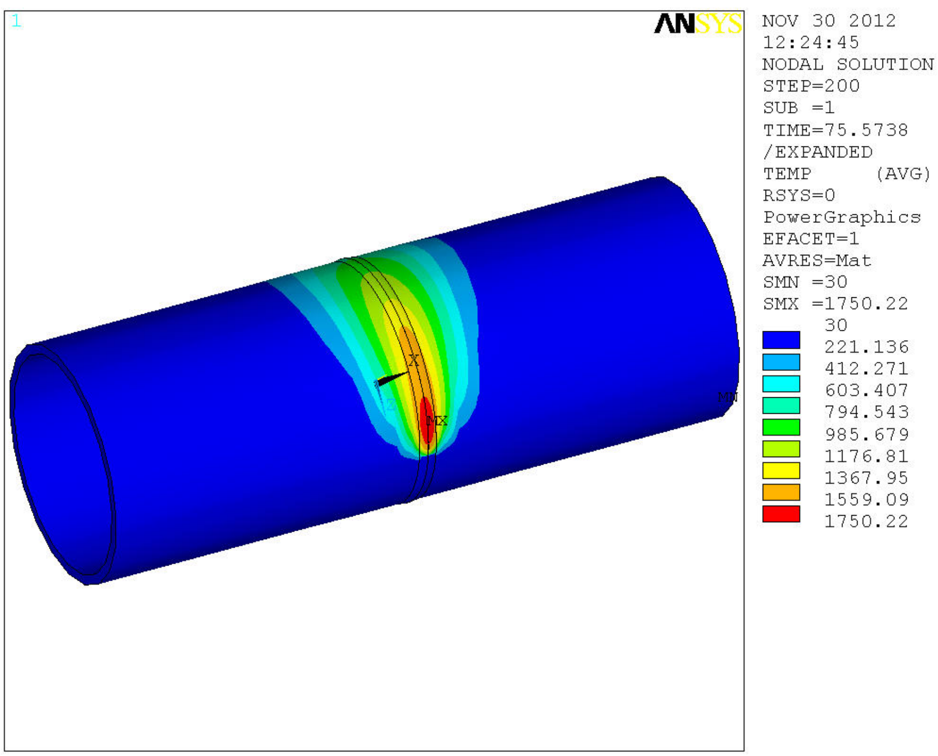

Figure 5.23 Temperature distribution (time= 75 sec)

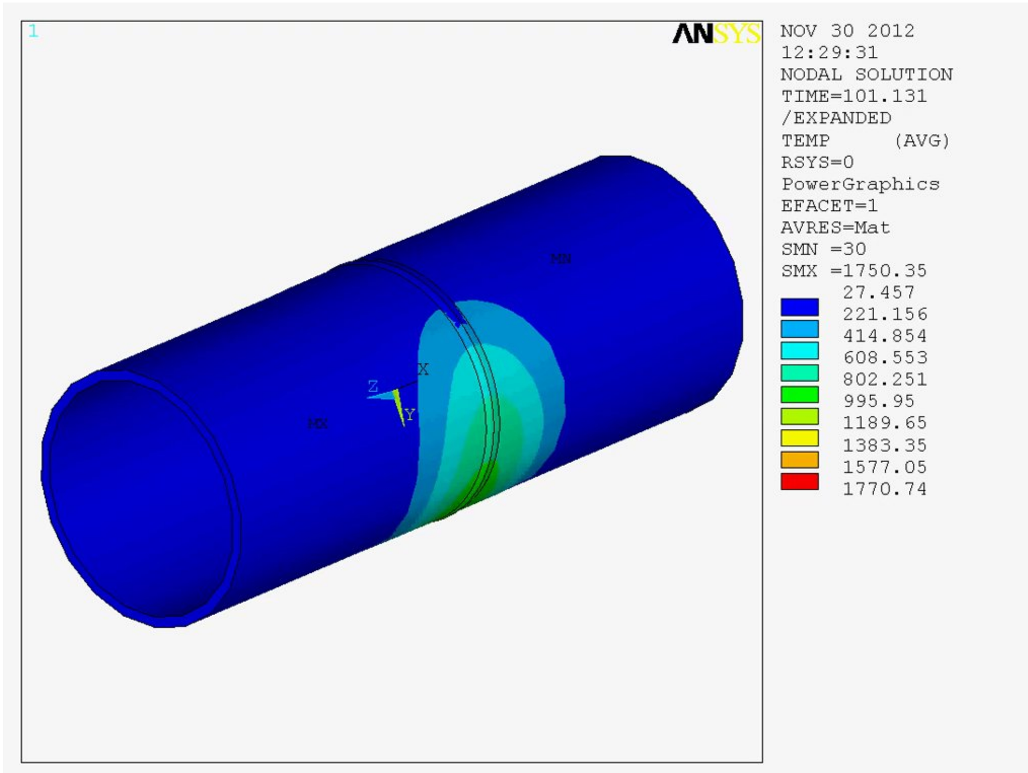

Figure 5.24 Temperature distribution (time= 102 sec)

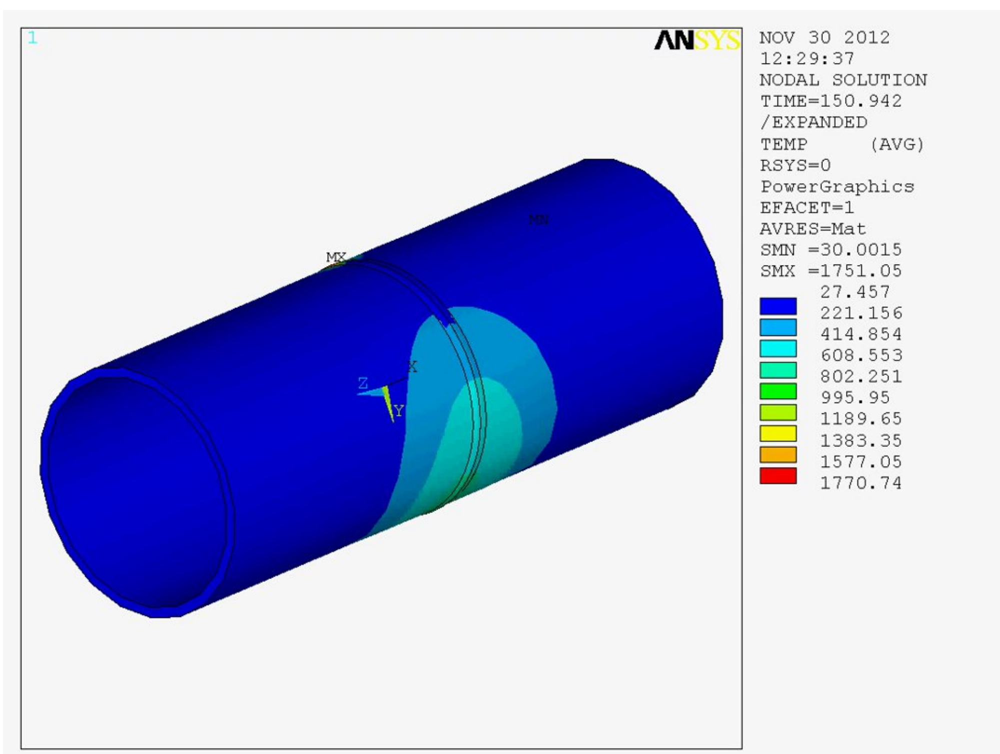

Figure5.25 Temperature distribution (time= 150 sec)

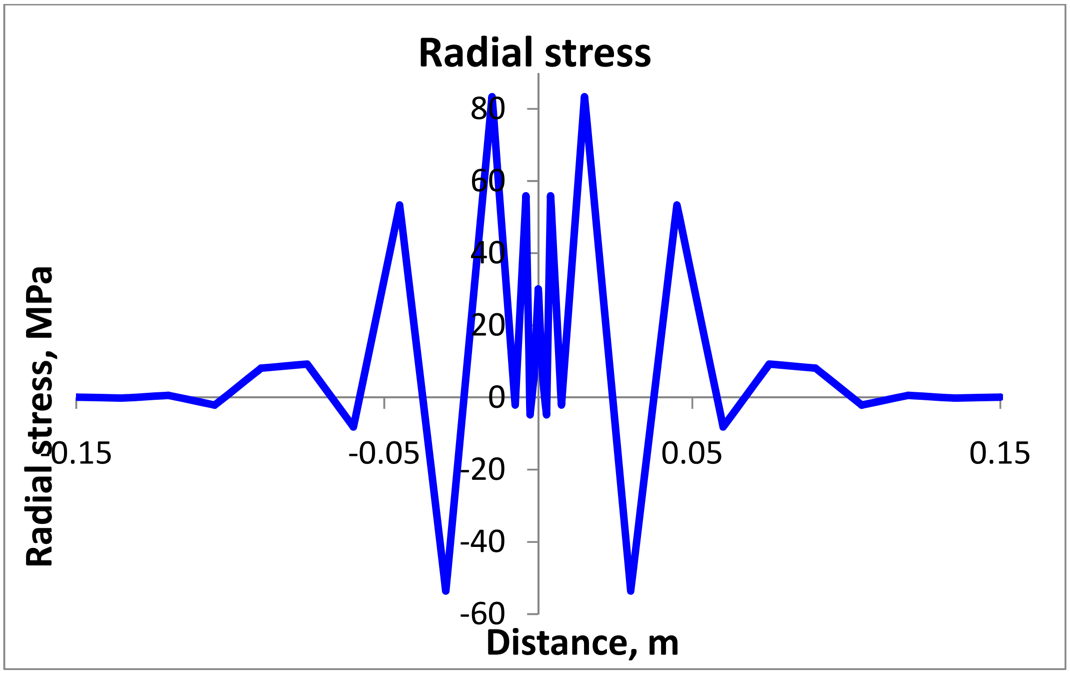

Figure 5.26 Radial stress

From the above figure, Radial stress is high near the butt weld joint and gradually decreased to the direction opposite to butt weld joint.

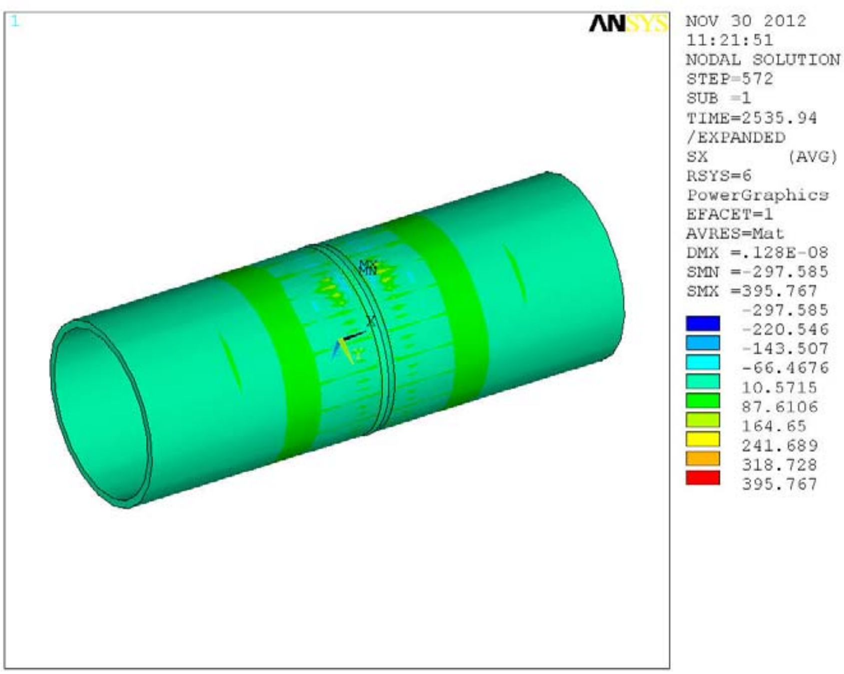

Figure 5.27 Radial stress - Contour plot

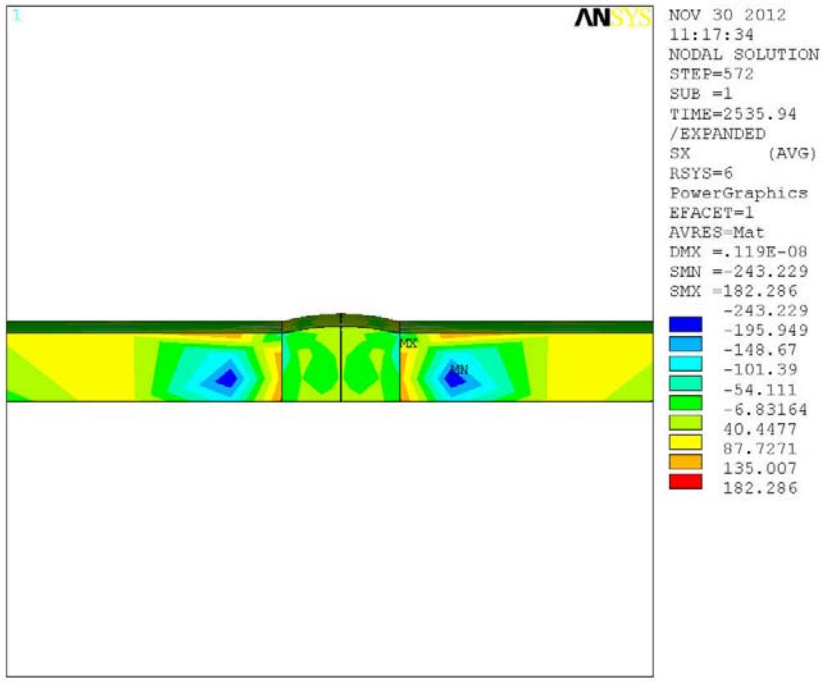

Figure 5.28 Radial stress - Contour plot Sectional view

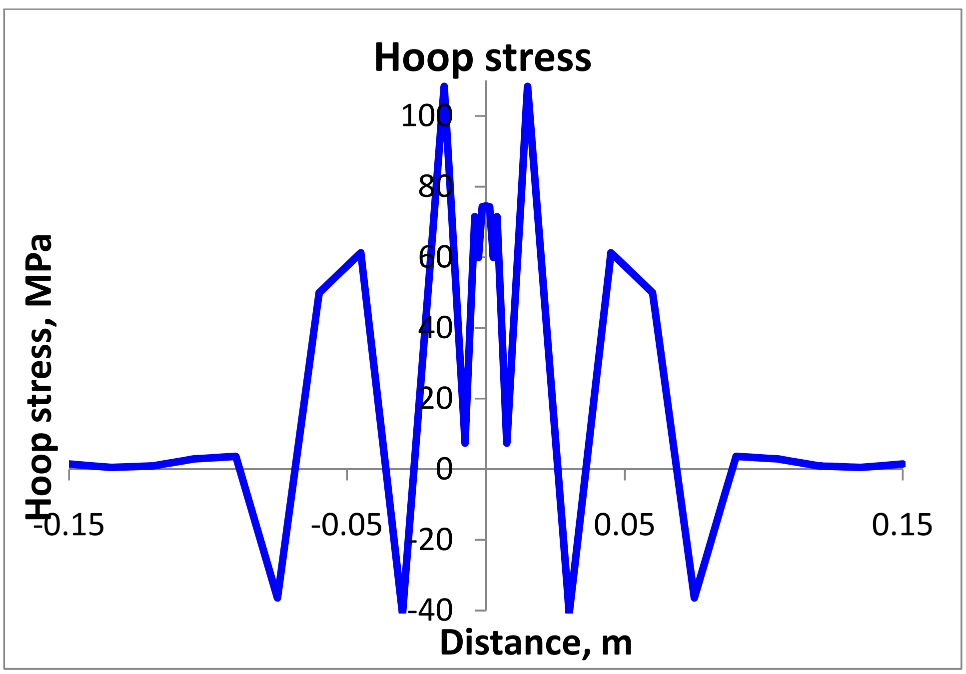

Figure 5.29 Hoop stress

From the above figure, Hoop stress is high near the butt weld joint and gradually decreased to the direction opposite to butt weld joint

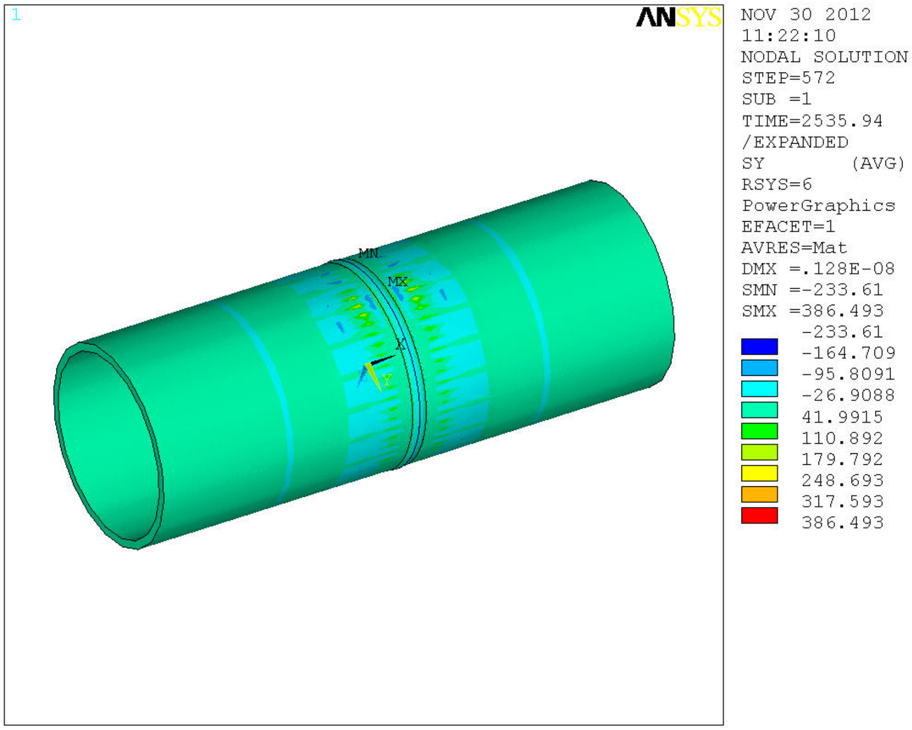

Figure 5.30 Hoop stress - Contour plot

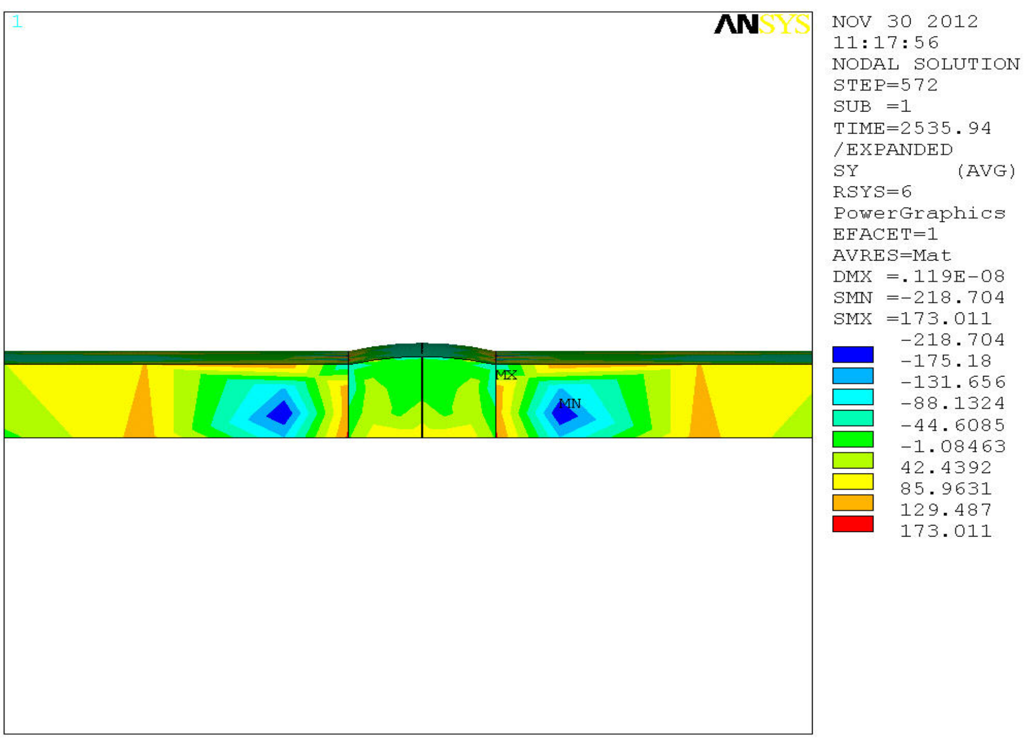

Figure 5.31 Hoop stress - Contour plot Cross Sectional view

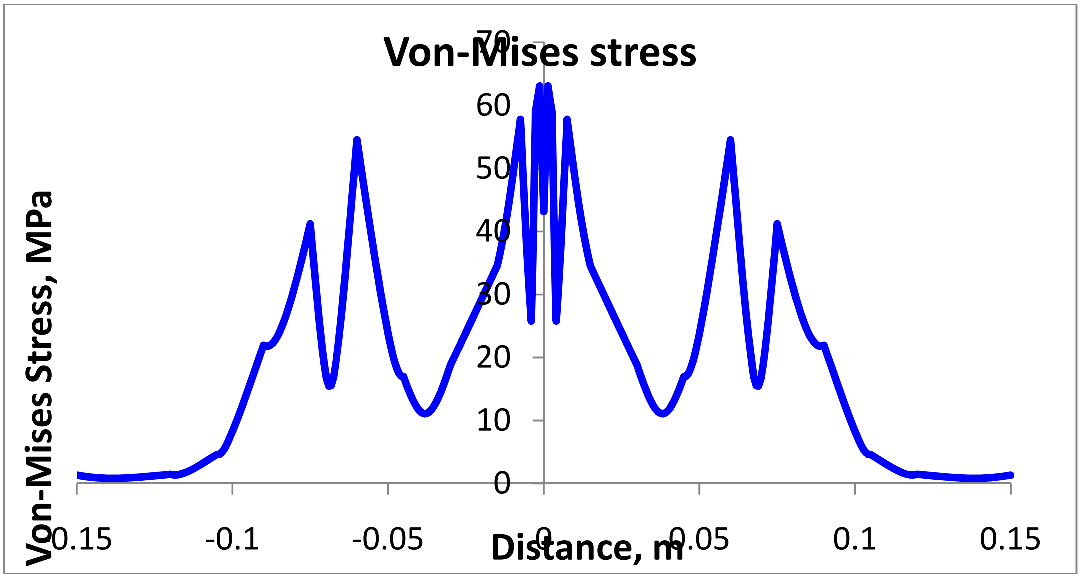

Figure 5.32 Von Mises stress

From the above figure, Von Mises stress is high near the butt weld joint and gradually decreased to the direction opposite to butt weld joint

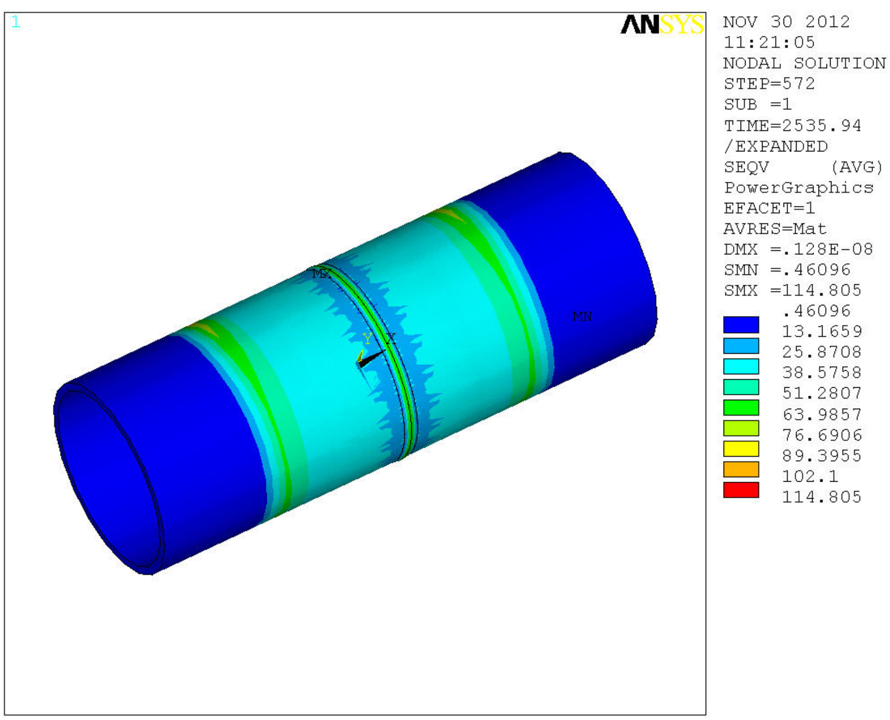

Figure 5.33 Von Mises stress - Contour plot

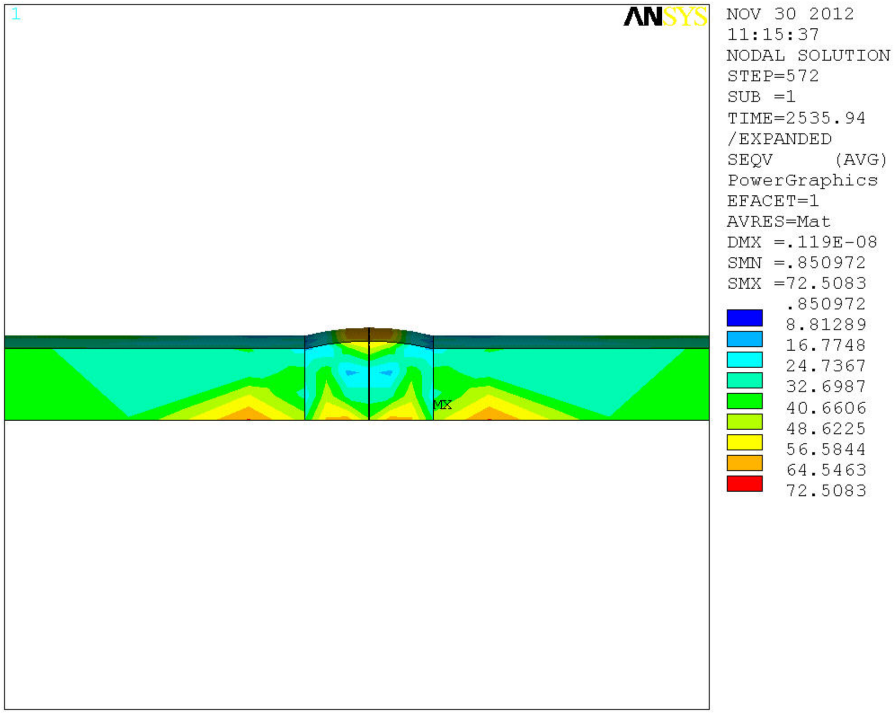

Figure 5.34 Von Mises stress - Contour plot Cross-sectional view

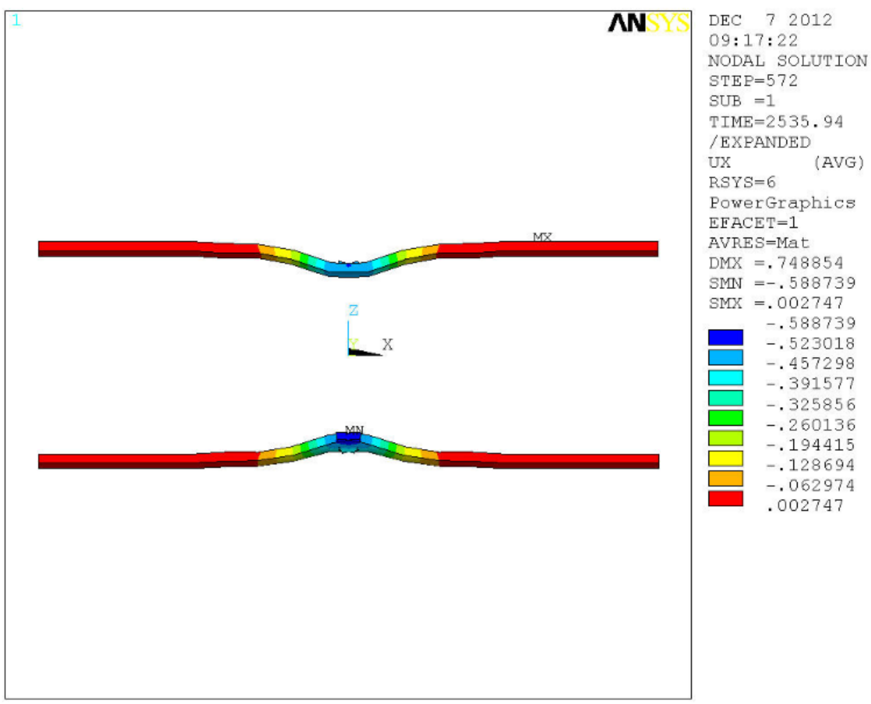

Figure 5.35 Deformation on Radial Direction.

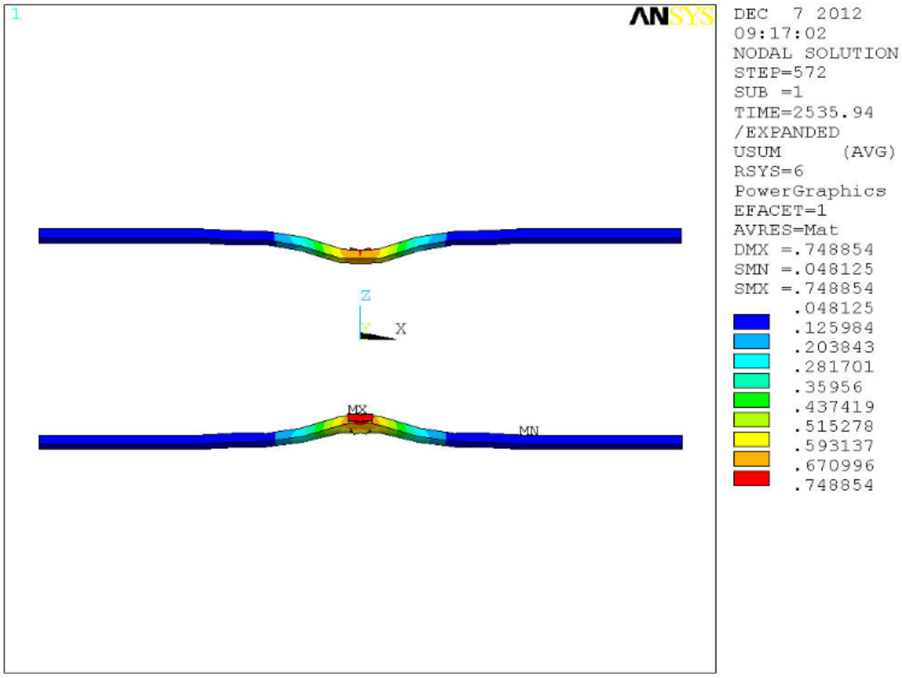

Figure 5.36 Absolute Deformation

5.2.3 Stress Comparison Plots

The below images show the various stress comparison between stainless steel and aluminum material for the same pipe structure.

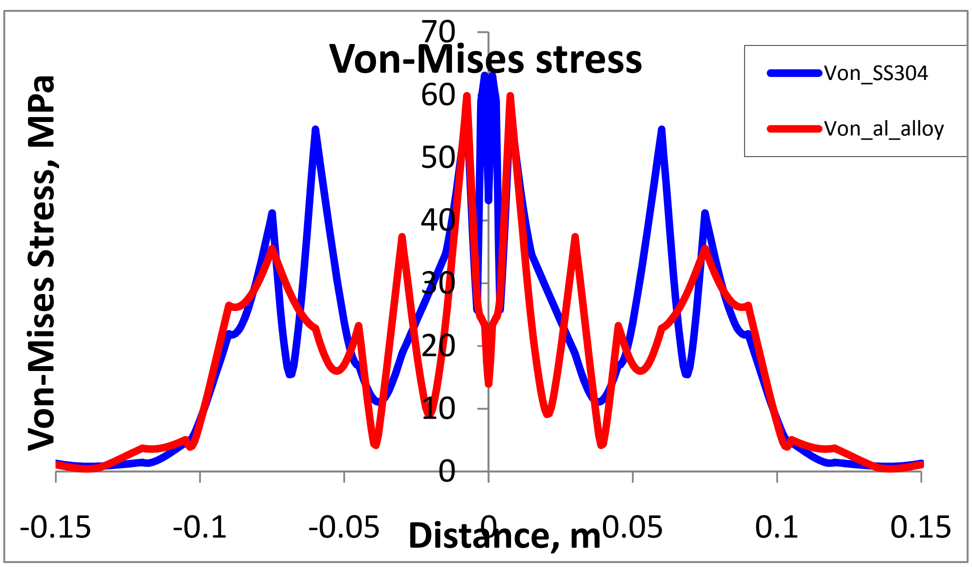

Figure 5.37 Von Mises stress comparison between Aluminum and Stainless steel

Von-Mises- Stainless steel residual stress is high comparing Aluminum pipe

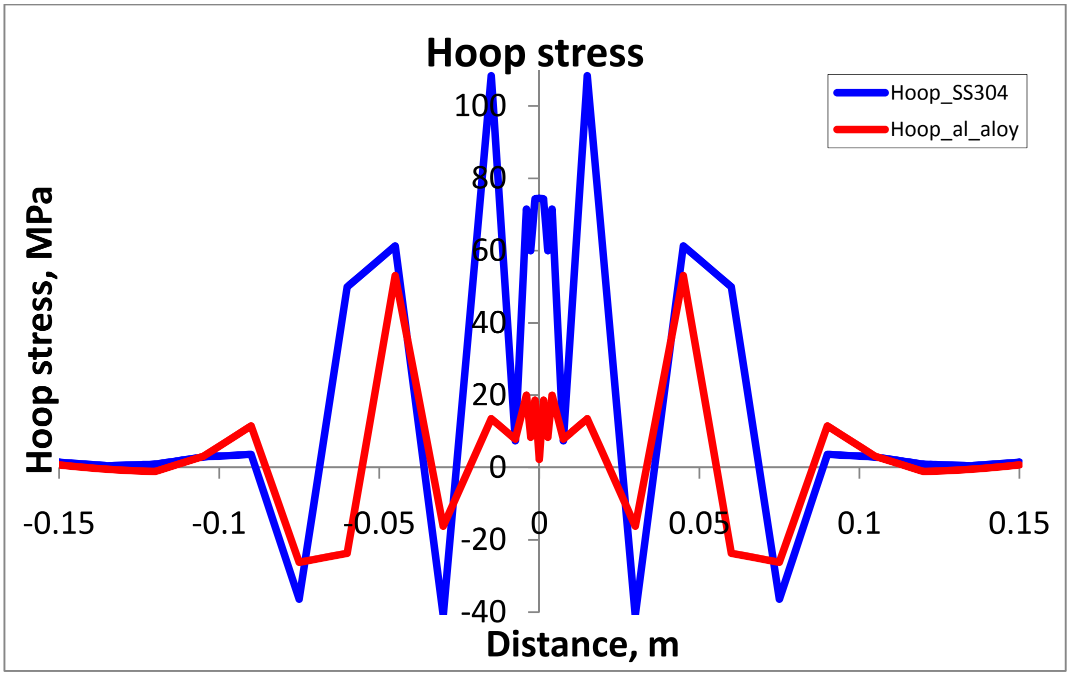

Figure 5.38 Hoop stress comparison between Aluminum and Stainless steel

Hoop direction Stainless steel residual stress is high comparing Aluminum pipe

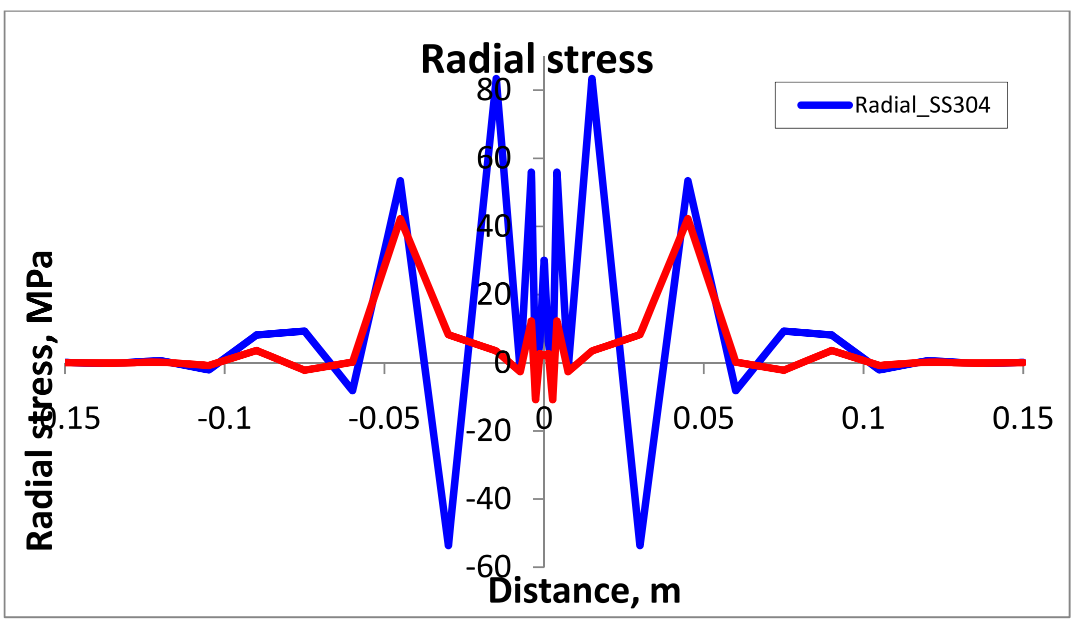

Figure 5.39 Radial stress comparison between Aluminum and Stainless steel

Radial direction Stainless steel residual stress is high comparing Aluminum pipel

5.3 Conclusion

Residual Stress : The amount of residual stress is high in stainless steel as compared with Aluminum. The reason is because of the high thermal conductivity of aluminum material.

Hoop Stress : The amount of residual stress is high in stainless steel as compared with Aluminum. The reason is because of the high thermal conductivity of aluminum material.

Von-MisesStress : The amount of residual stress is high in stainless steel as compared with Aluminum. The reason is because of the high thermal conductivity of aluminum material.

Workability and Ease of Use : While seeing workability and Ease of Use Aluminum pipe is experiencing good result than Stainless Steel due to residual stress stored is more.

Weight : Aluminum is lighter than Stainless Steel.

Corrosion: Aluminum is having greater resistance to corrosion. So it is used in Aircraft and Engine pats.

Cost : By comparing Cost, Even though Aluminum per pound is costly. But volume of the material is more that Stainless Steel

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