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EXPERIMENTAL AND NUMERICAL INVESTIGATION OF PLASMA-JET FORMING

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ABSTRACT OF THESIS

EXPERIMENTAL AND NUMERICAL INVESTIGATION OF PLASMA-JET FORMING

Sheet metal forming has found increasing applications in modern industries. To eliminate use of expensive tools during product development, thermal forming, a rapid prototyping process that is flexible enough to decrease costs has been developed. Thermal forming processes use a heat source to perform the required deformation mainly by creating a thermal difference along the thickness of the sheet. Gas flames, lasers and plasma heat sources have been used for sheet metal bending by thermal forming. An alternative to laser and gas flames, plasma-jet forming has been developed that uses a non-transferred plasma arc as a heat source. The plasma-jet forming system uses a highly controllable non-transferred plasma torch as a heat source to create the necessary thermal gradient in the sheet metal that causes the required plastic deformation. Various experiments to produce simple linear bends and other complex shapes have been conducted by using different scanning options and coupling techniques. A computer simulated model using finite element method is being developed to study key parameters affecting this process and also to measure the thermal transient temperature distribution during the process. A predictive model to relate the deformation to the temperature gradient for various materials is being developed. Simulation results that are in accordance to experimental observations will further improve this material forming process to be highly controllable and more accurate

KEYWORDS: Metal forming, Thermal forming, Laser Forming, Rapid prototyping,
Finite element method.

Sailesh Kumar Tangirala

08/24/2006

EXPERIMENTAL AND NUMERICAL INVESTIGATION
OF PLASMA-JET FORMING

By

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08/24/2006

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THESIS

Sailesh Kumar Tangirala

The Graduate School

University of Kentucky

2006

EXPERIMENTAL AND NUMERICAL INVESTIGATION
OF PLASMA-JET FORMING

THESIS

A thesis submitted in partial fulfillment of the
requirements for the degree of Master of Science in Mechanical Engineering
in the College of Engineering at the University of Kentucky

By

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2006

Dedicated
.....To My Parents

ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to Dr. Alan.T.Male for giving me the opportunity to work on such an interesting and challenging project. What I have learned from Dr. Male is far beyond my academic and research skills. The progress of this work would not be achieved without his guidance, support, encouragement and patience.

My special thanks to Dr. Keith Rouch for his unstinting support and guidance in every aspect of the simulation and helping me improve the work through his insights. I would also like to acknowledge the support provided by Dr. Marwan Khraisheh in vital parts of my research. I also thank Dr. Yuming Zhang for being on my committee and extending his knowledge and guidance. The invaluable suggestions provided by the committee members are gratefully acknowledged. I sincerely thank Mr. Jin Song for helping me with the technical aspects regarding the forming system during experiments.

The most valuable encouragement and support was provided by my family and friends which helped me succeed in this challenging endeavor.

Thank you all!

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CHAPTER I

INTRODUCTION

1.1 Motivation

Sheet metal forming technology is one of the most common methods of forming used in industry. Metal forming on a conventional basis involves hard tooling that performs with assistance from high power equipment. These methods, although they have a very low process time have many disadvantages. While high costs of tools increase the expense of forming during prototyping, thermal forming has emerged as an alternative to conventional metal forming of sheets that eliminates the use of any tooling and reduce costs, especially for prototyping and low volume production. It is a non-contact metal forming process that employs a heat source to induce necessary thermal distortion to bend the sheet metal. Thermal forming of sheet metals being the most flexible forming process, and is very similar to torch bending and straightening process used in ship building industry. With vast improvements in its process in a short time, thermal forming processes can soon find commercial applications in various industrial applications.

Thermal forming is a highly controllable and repeatable forming process that can be used to form complex shapes with minimal material degradation. Many of the process and material parameters were analyzed using laser heat sources both experimentally and analytically [2-22]. Plasma-jet forming process has been used as an alternative to lasers to provide a cheaper and faster means to bend sheets [23-30]. Bending behavior and processing effects were analyzed with changing material parameters. Although the major parameters resulting in process variability have been determined, there is a need to improve the process by investigating possible multi-pass techniques that will increase the bending with increased scans. A predictive model that will determine the stress behavior and temperature field distributions will also enunciate further advancements of this process.

1.2 Research Objective and Outline

Thermal forming applications and activities have been increasing for the past two decades with considerable efforts focused on making this process highly reproducible. As an alternative to mechanical forming methods, experiments and analysis of thermal forming systems using lasers and plasma heat sources have resulted in greater efficiencies and increased forming options. Although the mechanisms, process and product variables have been identified, greater emphasis on analysis and prediction of bending with respect to these parameters has to be performed. Multi-pass bending characteristics and resultant effects of material parameters such as strain hardening have to be investigated. This will require analyzing new techniques to form the sheet using continuous and discrete heating procedures that are supported by advanced simulations.

The fundamental theme of this dissertation is to improve the Plasma-jet Forming process by analyzing various methods that can be employed to increase the bending behavior. A Computational Model will also be developed in an effort to analyze the thermal stress behavior and predict the bending angle with increase in passes. Effect of continuous heating and discrete or alternative heating and cooling methods will be observed by experiments. Temperature and stress behavior during these processes will be predicted by using a thermo-mechanical finite element simulation tool. As the flexibility of a structure increases, linear approximations often do not accurately predict the behavior. Predicting non-linear behavior of such a flexible process will be a challenging task when the three dimensional mathematical model, material model and computational time are considered.

An experimental approach to increase the bending behavior with increased passes will be analyzed. Effect of continuous heating on the material will be determined. An alternate technique based on discrete heating and cooling in an effort to increase temperature gradient for better bending will be considered. Experiments will be performed to compare these continuous and discrete pass techniques.

To investigate the process capability of plasma-jet forming on sheets of large thickness, experiments will be performed to study the multi pass bending rate with varying thickness. Sheets of thickness from 0.8mm up to 3mm will be formed and relation between bending and process parameters such as torch speed, power and offset distance will be determined. Efforts will also be made to correlate these experimental data with simulation results so that effect of thermal stresses over bending rate can be accurately analyzed. A commercial finite element program ANSYS will be used to simulate and analyze thermo-mechanical model of plasma-jet forming.

1.3 Thesis Layout

This thesis consists of six chapters including the current introduction chapter. In Chapter II, a detailed literature review with past and present activities in thermal forming involving both lasers and plasma heat sources will be discussed. Mechanisms, simulations and experiments that have been published to date will be discussed to study possible options for further enhancement of this process. Chapter III consists of the details of the plasma-jet forming system and experimental investigations of process and material parameters on bending angle will be discussed. Details of finite element analysis using ANSYS will be discussed in Chapter IV. The thermo-mechanical simulation results will be analyzed to predict a relation between thermal gradient and bending. Also challenges related to material models and mathematical modeling for multi pass bending will be listed. Chapter V contains the overall summary and contributions made from this experimental and numerical investigation. Recommendations and future scope of this work will also be discussed in Chapter VI. An appendix with information regarding the finite element procedure for possible element shapes will be provided.

CHAPTER II

LITERATURE REVIEW

2.1 Background

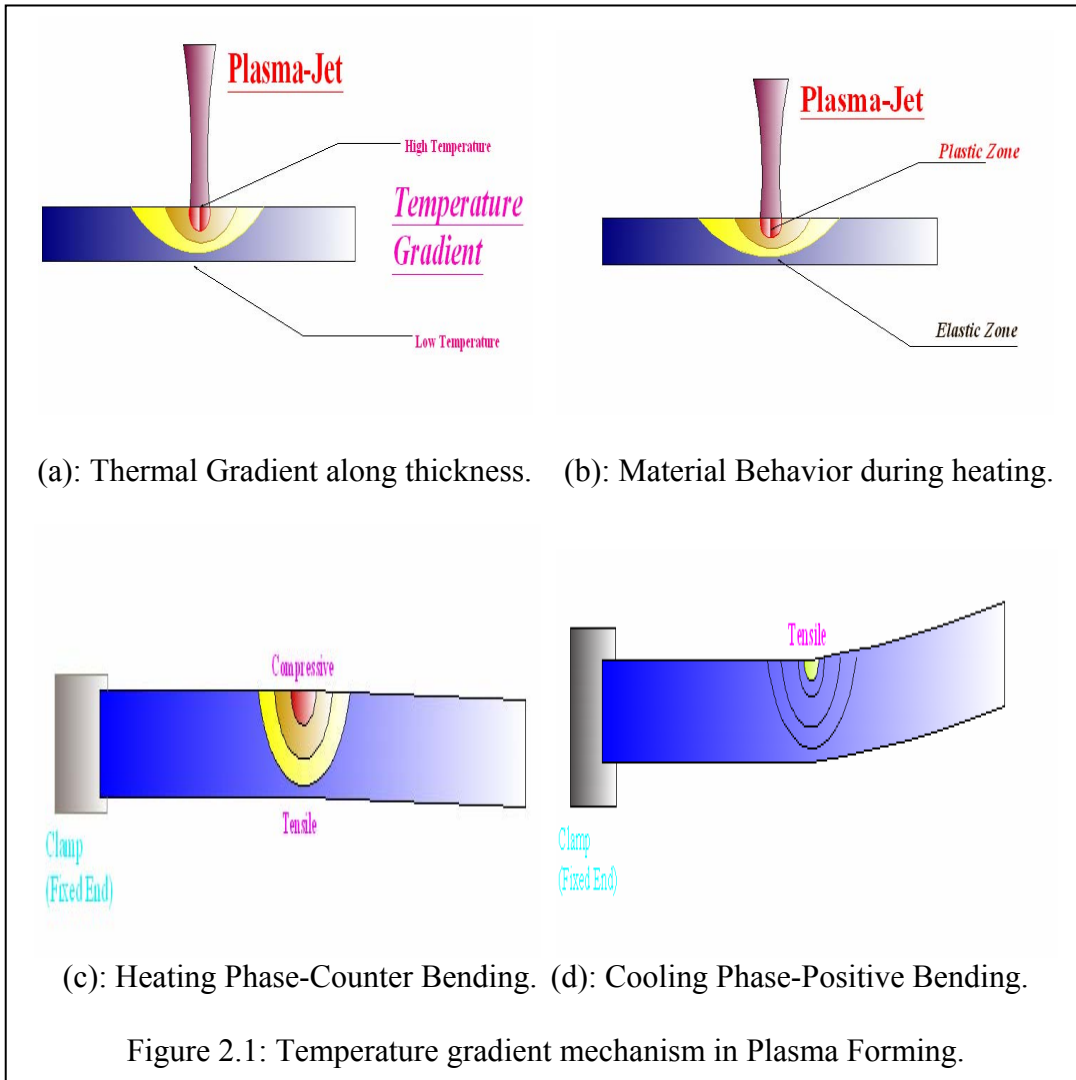
Metal forming in a conventional manufacturing environment involves use of heavy tooling and machinery that consumes high power. Thermal forming is a flexible forming technology that uses a heat source-gas flame, plasma or laser to form a sheet metal by inducing thermal stresses in the sheet instead of external mechanical forces. Thermal forming is a tool-less, non-contact material forming technology that overcomes the need for expensive tools as in conventional sheet metal bending processes. The major advantage of thermal forming is it being highly controllable and repeatable and that it can be used to form complex shapes even with brittle materials. Thermal forming is potentially applicable in rapid prototyping, low volume manufacturing environment.

2.2 Thermal Forming Mechanism

The concept of thermal forming emerges from thermal expansion and contraction phenomenon of metals. The localized heating of the metal tends to expand the metal, but under the influence of high temperatures when the expansion is constrained, compressive stresses are generated resulting in plastic deformation of the material in the heated region.

The basic thermal forming process involves a moving heat source that traverses a guided path (straight line or curvilinear) on the top surface of the sheet metal, to locally heat the sheet metal while the remaining sheet is at ambient conditions. A coolant is used on the bottom surface to create a necessary temperature gradient that generates thermal stresses in the sheet. The localized temperature changes enunciate plastic deformation along the heated zone thereby bending the metal plate.

This method of bending by application of differential temperatures is termed as *Temperature Gradient Mechanism*. The Temperature gradient mechanism has been found to be major reason for bending by Thermal forming [1][2][3][6][7][8][11]. Figure 2.1 illustrates the temperature gradient mechanism with respect to plasma-jet forming.



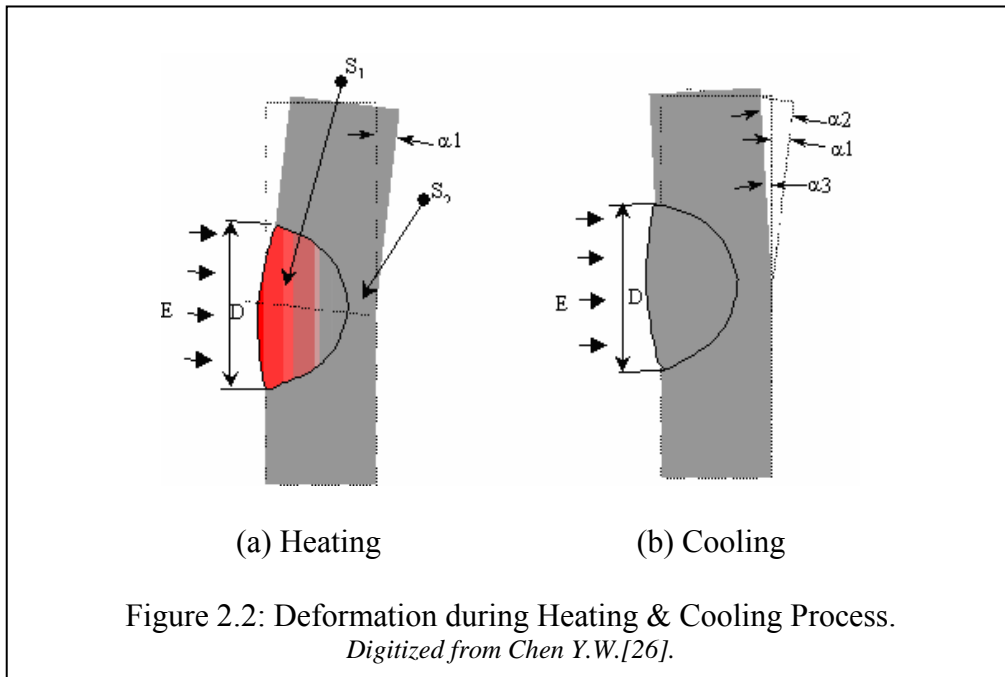
Thermal forming is basically a two-step process, the heating phase followed by the cooling phase (Figure 2.1(c) & (d)). The metal plate initially when heated bends away from the heat source (counter- bending) and later bends towards the heat source (positive bending) when cooled [1] [4][5][11][26].

Majority of experiments involved a cantilever beam like arrangement with the sheet clamped at one end. Some experiments involved the metal plates having supports on both ends and the unrestricted sheet was allowed to bend freely.

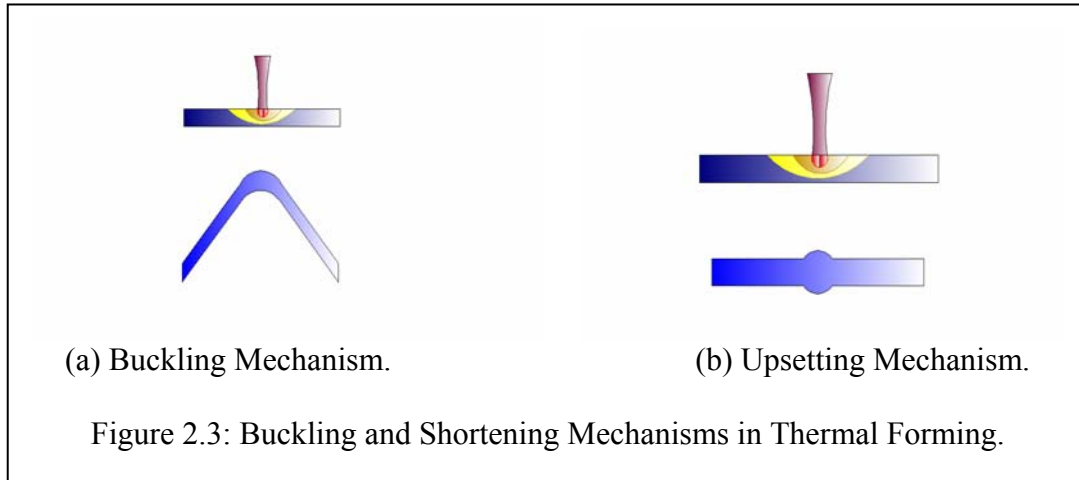
Bending away from the heat source occurs when the surface being heated along the bending line exhibits a convex hinge. This is mainly because of a high temperature on the top surface and a low temperature on the bottom surface along the heating line. As shown in Figure 2.2(a)

compressive stresses (S_1) and tensile stresses (S_2) generate on top and bottom surfaces respectively. The metal on the top surface being hotter tends to expand and the ambient temperature surrounding it tries to restrict the expansion thereby allowing it to bend away from the heat source.

Bending towards the heat source is said to be the second step of the forming process where the material on the top is in plastic state due to heating while the material on the bottom still maintains its elastic state. On cooling, contraction occurs in the sheet metal mainly in the plastic deformed heated zone and thereby bending the plate towards the heat source permanently. This mainly occurs due to lower yield stress of the material at higher temperatures than at low temperatures [1][4]. This helps in bending on cooling it further until the whole sheet reaches equilibrium (room temperature).



Apart from the temperature gradient mechanism, buckling and shortening (Upsetting) mechanism have been defined. Buckling occurs when the beam diameter is much larger than the sheet thickness and a low scanning speed is used. This results in a thermo elastic-plastic buckling in the material. The buckle creates a residual plastic strain causing the deflection. Shortening or Upsetting occurs due to an increased moment of inertia than that of the sheet material in the metal geometry that prevents buckling [21][8].



This increased moment of inertia could generate high energy in the metal plate in one step. Shortening generally occurs along the geometrical plane. Bending towards the arc is mainly due to temperature gradient mechanism when a high speed torch with a small beam width is used. Buckling allows the sheet to bend away from the arc and generally occurs when a slow moving heat source is used with a large beam diameter. Shortening or Upsetting happens with a slow moving beam and a small beam diameter. Shortening is the mechanism generally used to form tubes and bowls.

2.3 Heat Sources

Thermal Forming is a method of localized heating, used to generate thermal stresses that enunciate a permanent deformation in the material. This concept of localized heating or line heating is being used in the ship building industry for straightening long-bent metallic plates [1]. Gas Flame Torches was predominantly the only heat source used for flame straightening and altering weld structures until lasers came into existence.

2.3.1 Laser Forming

Over the past thirty years development of lasers has led to its application in manufacturing industry in a new way replacing many conventional techniques. Lasers were first employed as heat source for sheet metal forming in early 1980's by Masubuchi et al. [2]. It has been demonstrated that simple bending of sheet metals is practically possible and can be extended to

study the possible forming of complex structures. Studies have been performed to analyze the effect of residual stresses and deflections in complex shapes formed by laser bending using thermo-mechanical Finite Element Simulations at M.I.T, U.S.A [2][3][4]. The effects of temperature field distribution and its influence on thermal strains have been determined and were followed by parametric studies in an effort to optimize the performance characteristics.

Lasers provided a highly controllable heat source that could rapidly heat metallic surfaces. Further investigations on the effects of Laser Bending on material degradation, surface effects, mechanisms and investigations of 2D and 3D complex shapes have been performed by Vollertsen, Geiger, et al in Germany.[5] [6] [8]. Laser forming process was modeled using both finite difference and finite element methods [7]. Based on these simulations Vollertsen et al. suggested an empirical model to predict the bending angle as a function of material used and laser heat source properties [9]. Application of Laser forming in various fields was investigated by Frackiewicz et al. [10][11].

Many complex structures including tubes, pipes and utensils were produced with laser bending equipment under a highly controllable manufacturing environment. These research activities were performed on various materials of varied thickness.

With extensive experiments been performed to identify the effect of process variables such as the scanning speed, beam diameter and power, determining the controllability and repeatability of the process was to be evaluated. Thomson and Pridham have investigated the improvement of the manufacturing control parameters for laser forming by the application of closed loop controls [12]. The deformations of the sheet metal were analyzed to determine optimum forming parameters. Kyrsanidi et.al. have developed a valid numerical model for the laser forming process of steel components by using a coupled transient thermal-structural finite element analysis.[13]. Multi-scan laser forming techniques for analysis of edge effects and bending angle per pass for three-dimensional thin plates have been studied[14]. Convex laser forming techniques and its application in forming tubes have also been investigated [15] . Finite element simulations to study the strain rate effects on bending with increase of number of passes was also performed.

The focus in early 1990's was to develop and automate a highly precision closed loop control for laser forming that could improve the performance and help in analyzing the process variables to determine their effects on final deformation of the workpiece [9][10][11][12][14]. In the late

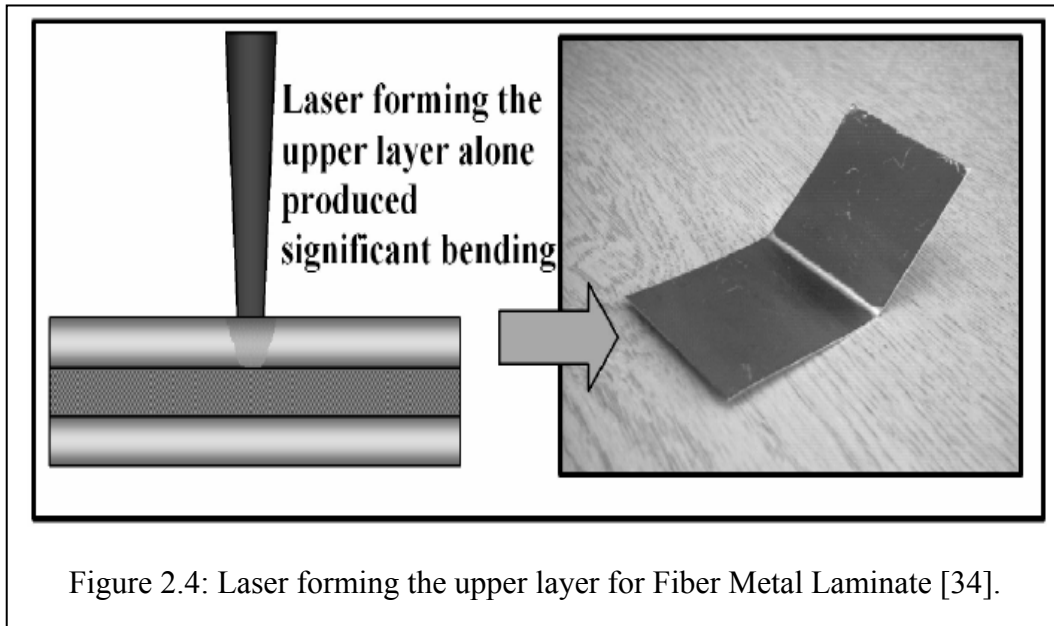
1990's, the effects of process parameters of a laser induced line heating equipment were studied on various materials such as Inconel, stainless steels, Aluminum alloys, Low carbon steels and also Titanium alloys [16][17]. The major work done until the early 21st century using the Laser Line Heating method involved analysis, optimization of the control system and the forming process so as to predict the bending angle and improve the process to form complex shapes. The thickness of sheet metals under test varied from 0.7mm to 3mm with various scanning methods and torch speeds. All the experiments were carried out using both low (Nd:YAG) and high (CO₂) powered lasers. These laser systems require additional safety norms from highly destructible reflections.

Recent advancements in laser forming involved experiments and analysis for its applicability in ship building industry. Sheet metal plates of thickness up to 6mm were formed to determine the capability of laser line heating for large ship structures [18][19][20][21]. The transient temperature fields and the bending angles were predicted for ship building structures using finite element method. It was observed that the bending angle per pass for plates of thickness varying from 3mm to 6mm was in the range of 0.8 degrees to 2 degrees per pass depending on the scanning method and velocity[22].

Much of the research activity on laser forming for ship structures is being done at University of Liverpool, U.K. and Penn State University, U.S.A. Numerical modelling and optimization of laser forming process for stainless steel circular sections has also been studied[46].

Some of the modern day research in laser forming is performed to study the implementation of this method in shipbuilding, automotive, micro-electronics and materials engineering. Microstructural analysis to study the strain rate effects on the flow stress and forming efficiency are also being analyzed[23][24]. The variations of the bending angle with number of passes, the total bending angle and bending angle per pass were determined [25].

Laser forming is also being used to form fiber metal laminates that are generally of very high strength and very difficult to form because of their construction. These materials are being tested for application in aerospace industry because of their significant weight reductions (strength to weight ratio). Multi pass laser forming on polyamide fiber metal laminates was investigated and studies about the material integrity and high speed formability for complex shapes are being performed[34].



2.3.2 Plasma-Jet Forming

As an alternative to lasers, plasma-jet forming was used as a cheaper and viable thermal forming method.[1][26][27][28]. A Non-transferred plasma torch has been used to create an arc that has a considerably higher heat transfer efficiency than the Lasers. The plasma-arc heat sources will also be able to produce higher temperatures at a faster rate than the lasers. The low powered plasma arc was used as a heat source and a compressed CO₂ gas was used as a coolant. The plasma arc is a highly controllable heat source that moves along a predetermined line and generates the required thermal gradients to obtain bending without having a major effect on the material degradation.

The processing effects of the plasma system were analyzed with scanning speed, standoff distance and cooling rate as variables[29]. The physical properties and effect of material properties were also investigated and it was found that with the increase in number of passes, hardening along the heat affected zone had increased although not to a high value[30].

The plasma scans were performed on four different materials(Mild Steel, Stainless Steel, Copper and Aluminum) of thickness 0.8mm. The effects of material parameters such as the thermal conductivity, thermal expansion coefficient were analysed[26][30]. It was found that a high temperature heat source on the top surface and a coolant on the bottom will bend the plate

towards the heat source whereas a low temperature heat source and no coolant will bend the sheet away from the heat source. It was also observed that the travel speed has significant effect on bending and surface temperatures of the sheet. A low scanning velocity and low thermal conductivity will heat the metal surface faster and thereby ensure higher thermal gradient with a precaution that the melting point is not reached. A higher velocity will thereby produce less surface temperatures and thereby less temperature gradient resulting in less bending.

Thermal conductivity of the material is found to be the decisive factor in determining the bending angle using plasma-jet forming. In recent years finite element simulations on plasma-jet forming were performed to study the effect of temperature field distribution and thermal stresses on bending[31][32]. The influences of thermal and mechanical parameters on the sheet metal geometry were analysed and the effect of the plasma arc power on the thermal gradient and surface temperature was investigated. It was found that arc power and scanning velocity are two major parameters that control the bending angle and forming accuracy. Current input forms a vital characteristic on which the plasma-arc power is dependent. Hence many experiments have been conducted by using the combination of current input and torch speed such that optimum bending angles are obtained by efficient use of the process variables (resources) available. A detailed overview of the developments of thermal forming have been incorporated in various articles published in the proceedings of IWOTE'05[33]. Present developments in thermal forming (mainly laser forming) have been discussed and the future directions of its growing applications was perceived.

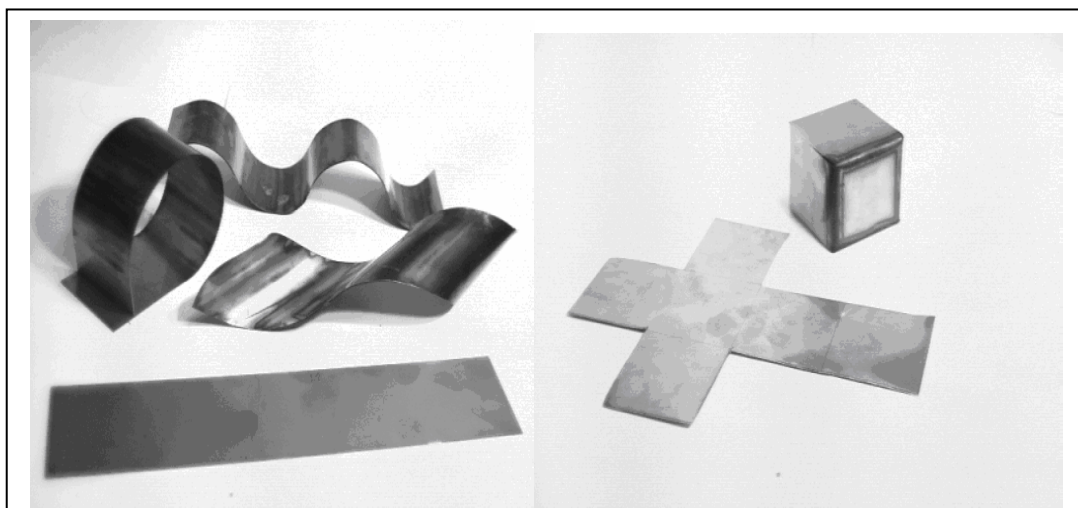


Figure 2.5: Bending samples using Plasma-jet Forming
Digitized from Chen Y.W.[26].

2.4 Discussion

Plasma-jet Forming has been a better alternative to Laser forming as it could reduce costs. Plasma arc is capable of producing higher temperature gradient and higher surface temperatures in lesser time with fewer number of passes when compared to Laser because of its high heat/energy transfer efficiency. Also, use of plasma will eliminate any requirement of absorptive coating like graphite. Plasma forming is a cheaper and safer method to employ when compared to lasers. Plasma forming finds its place in almost all the thermal forming applications. When forming efficiency is considered, Plasma-jet forming was found to produce a higher bending with a low powered system and fewer number of passes. Laser forming is more advantageous in electronics and micro forming where relatively higher precision is required.

Efforts have been made in optimizing the process by considering different ways of heating and cooling of the metal plate with both laser and plasma heat sources. Present day research in thermal forming involves validating its applications in electronic and ship building industry.

Hence this dissertation will mainly focus on improving the existing Plasma-jet forming process enabling a greater control and increased bending behavior. Experimental investigations will be performed to examine the bending behavior and the effect of various forming options with alternating heating and cooling methods. A computational model will be generated using a finite-element numerical simulation tool to analyze both thermal and structural behavior with respect to the variations in both process and physical parameters. The temperature field distribution and the stresses leading to bending will be investigated with respect to the thermal gradient mechanism.

CHAPTER III

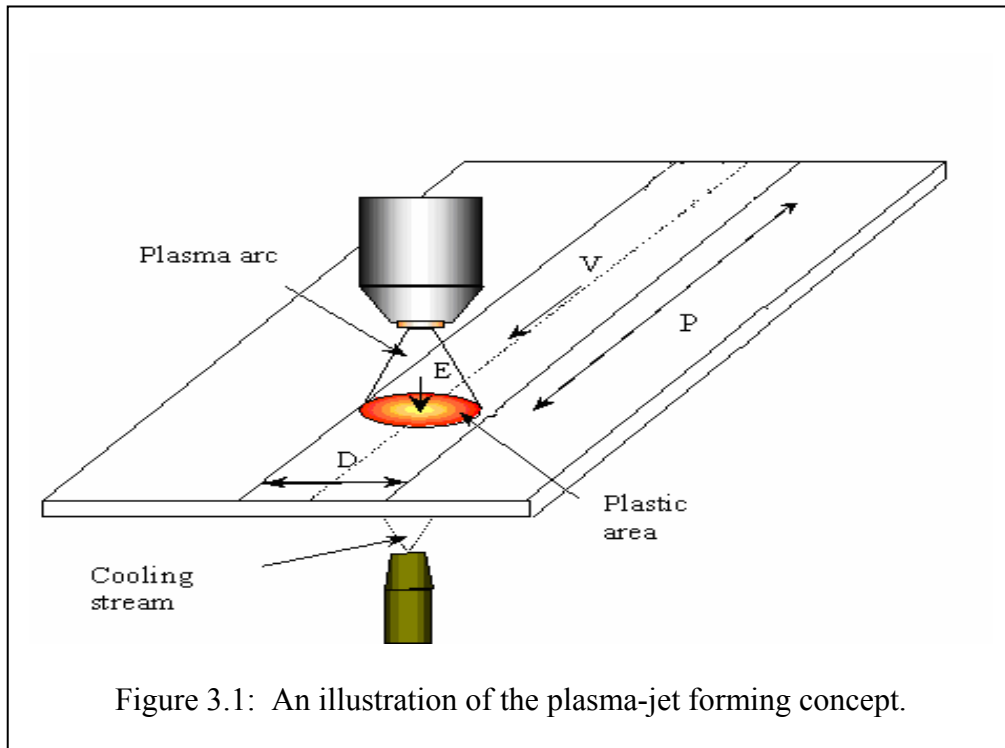
EXPERIMENTAL INVESTIGATION

3.1 Background

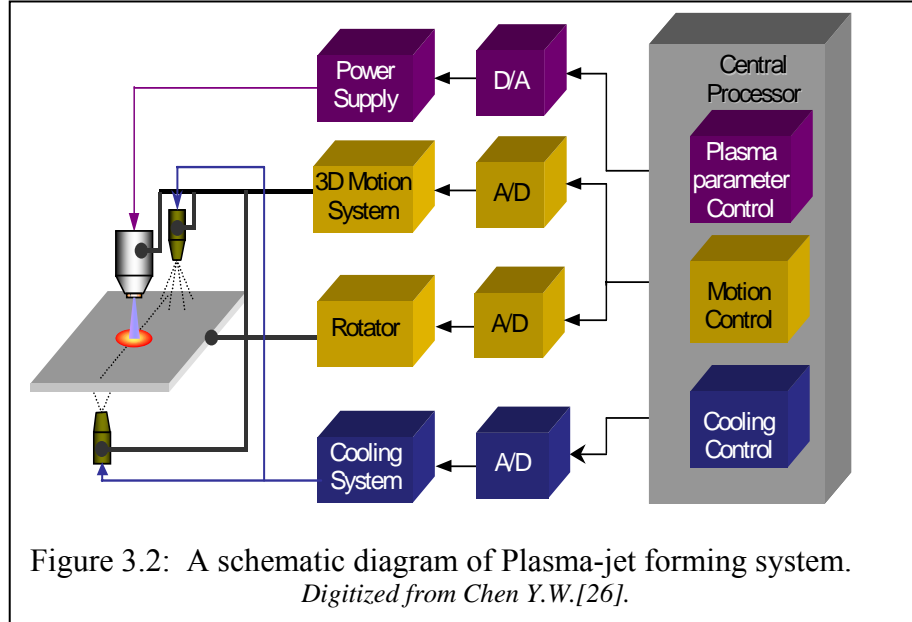
Earlier experimental investigation of plasma-jet forming involved use of a constant thickness sheet (0.8mm) to study the bending behavior of various materials [26]. Stainless steel (SS304), low carbon mild steel, Aluminum (Al 6061) and copper (C11000) alloys were used to analyze the scope of plasma jet forming. Correlation between the forming process parameters and bending were established. The influence of material physical parameters was also analyzed. All these materials were subjected to a constant power input subjected to line heating by continuous passes. While the bending behavior of these materials emphasized on thermal conductivity to be the major deciding factor, various forming options such as alternate heating and cooling, variable power line heating have to be considered. Also to analyze possible chances of increase in bending, influence of sheet thickness on bending is to be analyzed. Majority of the discussion in this chapter will involve observations made from experiments using alternate line heating methods where intermittent heating and cooling cycles will be analyzed. Effect of heating followed by rapid cooling after two cycles until 10 heating cycles will be determined and compared to continuous heating method. SS304 sheets of thickness 2mm and 3mm will be studied so that the effect of thickness on thermal bending may be determined. Magnesium alloy AZ31 will also be formed to investigate its forming capability by the application of plasma line heating.

3.2 Plasma-jet Forming System.

The plasma-jet forming system mainly consists of a non transferred plasma torch as a moving heat source that scans through a predetermined path with a coolant at the bottom thereby creating necessary thermal gradient required for bending as shown in the figure below.

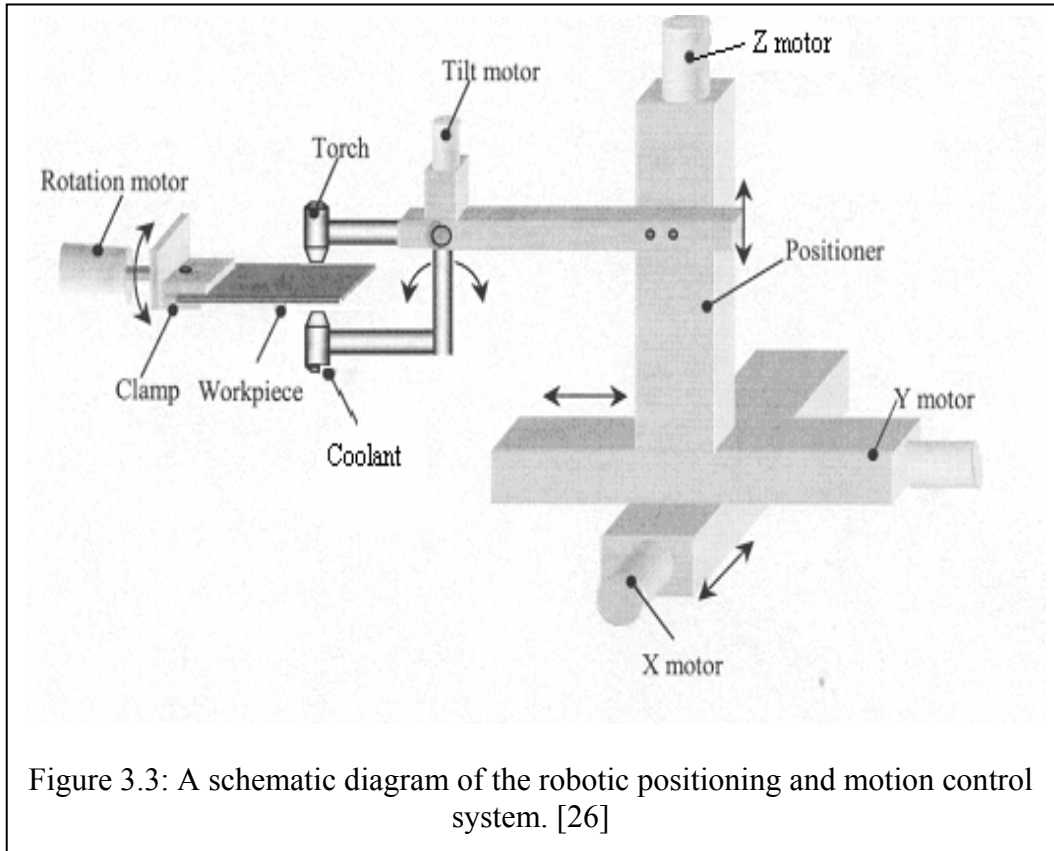


The sheet is clamped at one end and the other end is left free to enable a cantilever beam like arrangement. Experimental design of this system involves use of an automated robotic system to control the speed, distance and direction of traverse of the torch and cooling jet. A non transferred plasma arc torch is powered to generate required heating stream. The positioning of the torch, its motion and other parameters are controlled by an external workstation.



The workstation mainly contains control software that is used to set major parameters required for the forming process. It helps in automating the multi-pass forming process. A manual control function is also enabled to help the operator adjust the position of the torch and its movement. The motion control system is used to control the tilt and direction of motion of the torch. It is also used to control the rotation of the workpiece clamp. The positioning system is a three-dimensional system used to move and locate the torch such that the plasma jet is always perpendicular to the work piece along the line of heating. The positioning system mainly consists of a three degrees of freedom cartesian robotic system as the body that enables to move the torch in X, Y and Z directions respectively. Servomotors connected to each positioner help in the movement of the positioning system along the Cartesian axis. The arm of the robot has a single degree of freedom and is fixed with a tilt motor that helps in tilting the torch so as to maintain perpendicularity with the workpiece.

The workpiece clamp is provided with a 360 degree rotational capability along the XY plane. The torch is provided with a raster motion in the Y direction so that surface damage or melting of the workpiece can be avoided. All these parameters as input are controlled by the control software I/O interface programmed using Visual C++ and ActiveX tools.



The table below contains the maximum range of major process parameters involved in plasma-jet forming system.

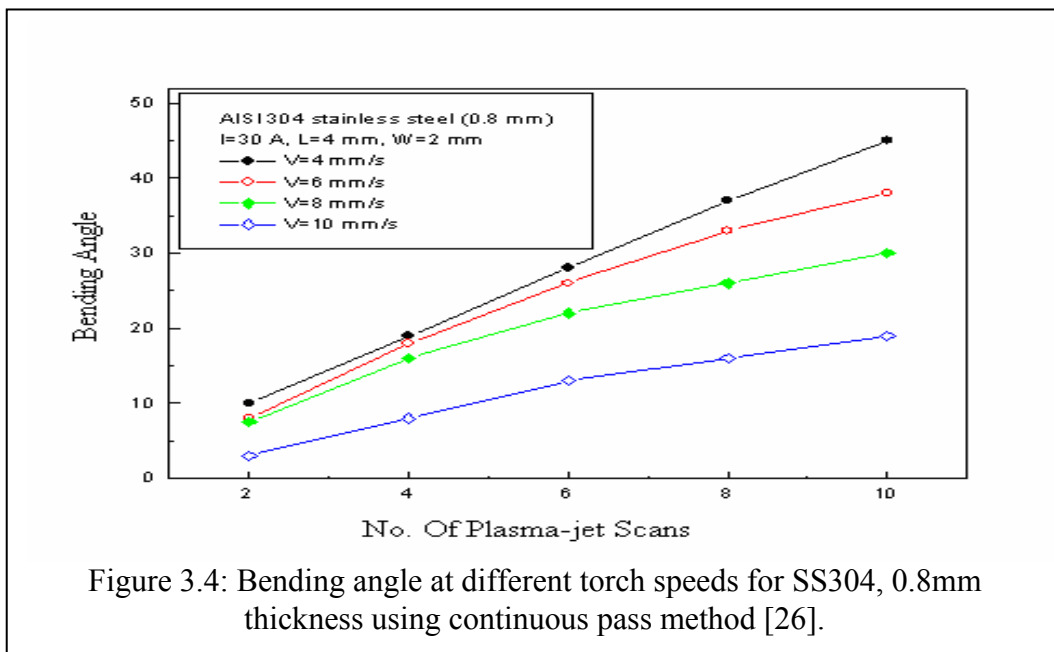
Table 3.1: Range of process parameters in the plasma-jet forming system.

Parameters	Range
Plasma-jet current	1 A-100 A
Cooling jet flow rate	0 L/min - 50 L/min
Travel speed	1 mm/s - 15 mm/s
Stand off distance	1 mm – 11 mm.
Beam diameter	1.5 mm – 4 mm
Y-direction traverse distance	1 mm – 100 mm
Torch tilting angle	1° - 60°
Clamp rotation angle	1° - 360°

The process parameters were standardized to optimize the forming capability for a 0.8mm thick sheet metal [26]. The plasma jet current of 30A, cooling jet flow rate of 19 L/min and torch speeds from 2 mm/s to 10 mm/s were used in majority of experiments. A constant orifice diameter of 2 mm was used with a standoff distance of 4mm. The Y-direction traverse of the torch was limited to a maximum of 10mm and could be altered based on the width of the workpiece used. The maximum torch tilting angle was set to 15°. The vibration amplitude range was 0.5mm to 6mm. The vibrating frequency is between 0 to 4Hz. The size and shape of the workpiece will mainly determine the exact parameters to be used at the time of operation of the forming system. The bending angle of the workpiece has been measured manually using a protractor with an error of $\pm 0.2^\circ$.

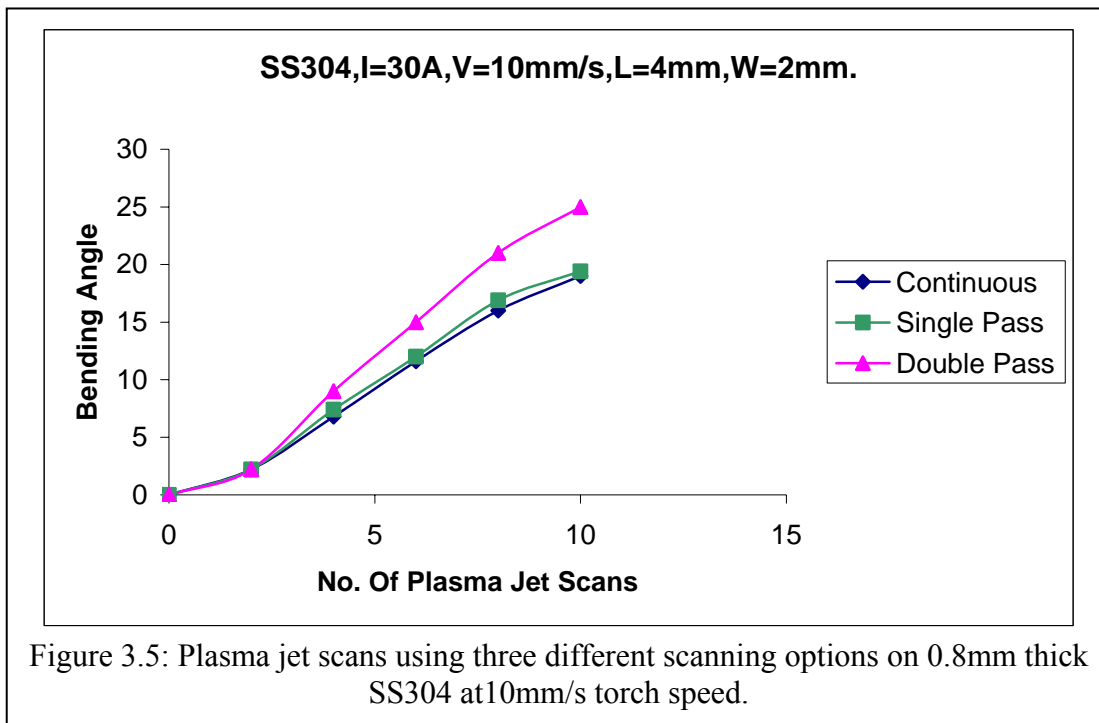
3.3 Effect Of Different Scanning Methods

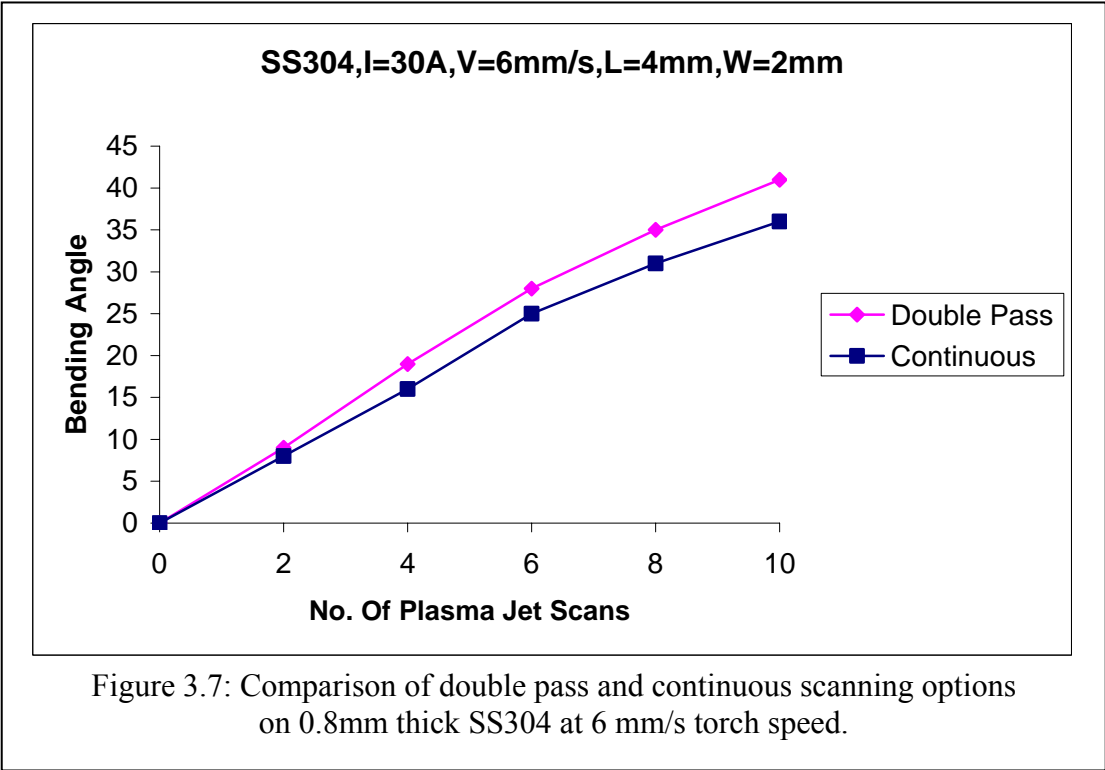
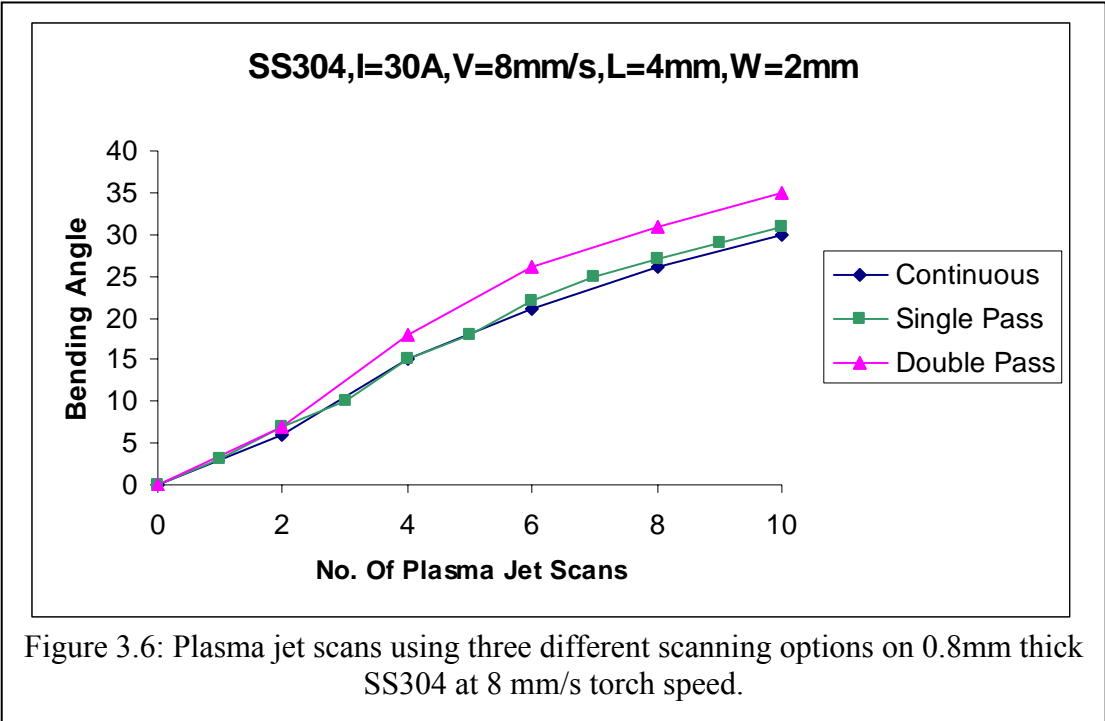
The forming method used for experimental investigations was predominantly a continuous pass method where the plasma torch was allowed to traverse a predetermined path for given number of cycles. The workpiece was later allowed to cool down to ambient temperature. One pass is defined to be completed when the torch starts at a specific point, moves to the other end and again traverses back to the original point. Hence one pass consists of forward and return cycle together. On an average 10 passes were performed to study the bending behavior by altering various process parameters. Thermal bending process mainly follows the temperature gradient mechanism to allow sufficient thermal stresses to be generated that enunciate a plastic deformation. The continuous pass method was used on four different materials by varying the process parameters to determine their effect on bending. The stand off distance, current input, beam diameter and torch speed mainly constituted the process parameters for these experiments.



Large bending angles with fewer passes can be obtained if a constant temperature difference between top and bottom surfaces is maintained. To achieve this, the material needs to be cooled down and again reheated to almost the same surface temperature in the next pass. This will not only enhance the material properties but also help in maintaining a consistent thermal gradient in each and every pass. In order to investigate a possible increase of bending angle in a multi-pass plasma-jet forming environment, effect of single pass and double pass scanning methods have been investigated.

In a single pass method, the plasma torch is allowed to traverse one pass and then the material is cooled rapidly with the help of coolant at the bottom surface to rapidly decrease the temperature to the ambient conditions. The material is reheated for another pass and the process is continued until predefined number of passes are completed. A double pass method is similar to the single pass method with the difference being in number of plasma irradiations being followed. The material is cooled to room temperature after two passes are completed in a double pass method. Experiments have been conducted on SS304 and low carbon mild steel sheets of dimension (130×50×0.8) mm. Comparison of double pass and continuous pass methods was performed to study any possible improvements in bending.





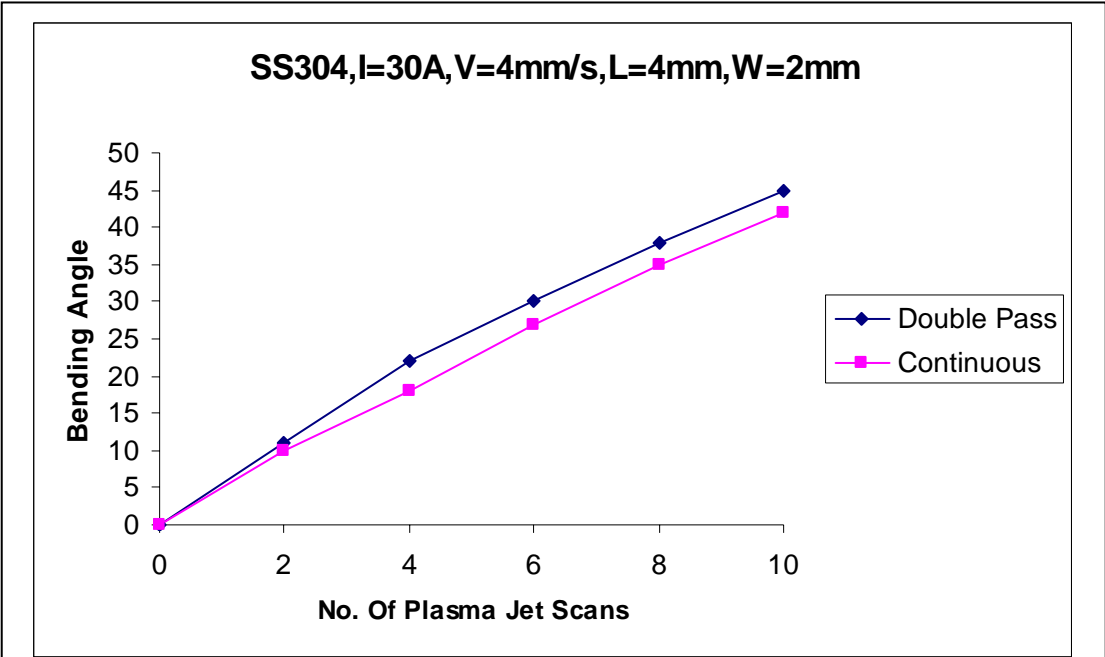


Figure 3.8: Comparison of double pass and continuous scanning options on 0.8mm thick SS304 at 6 mm/s torch speed.

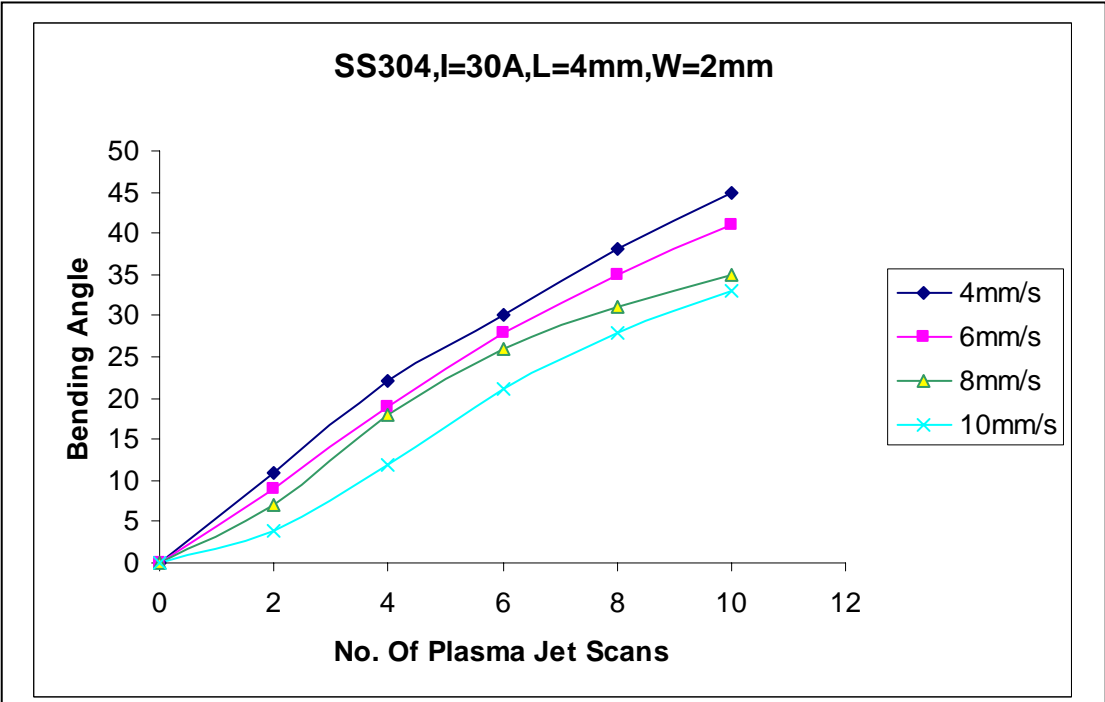
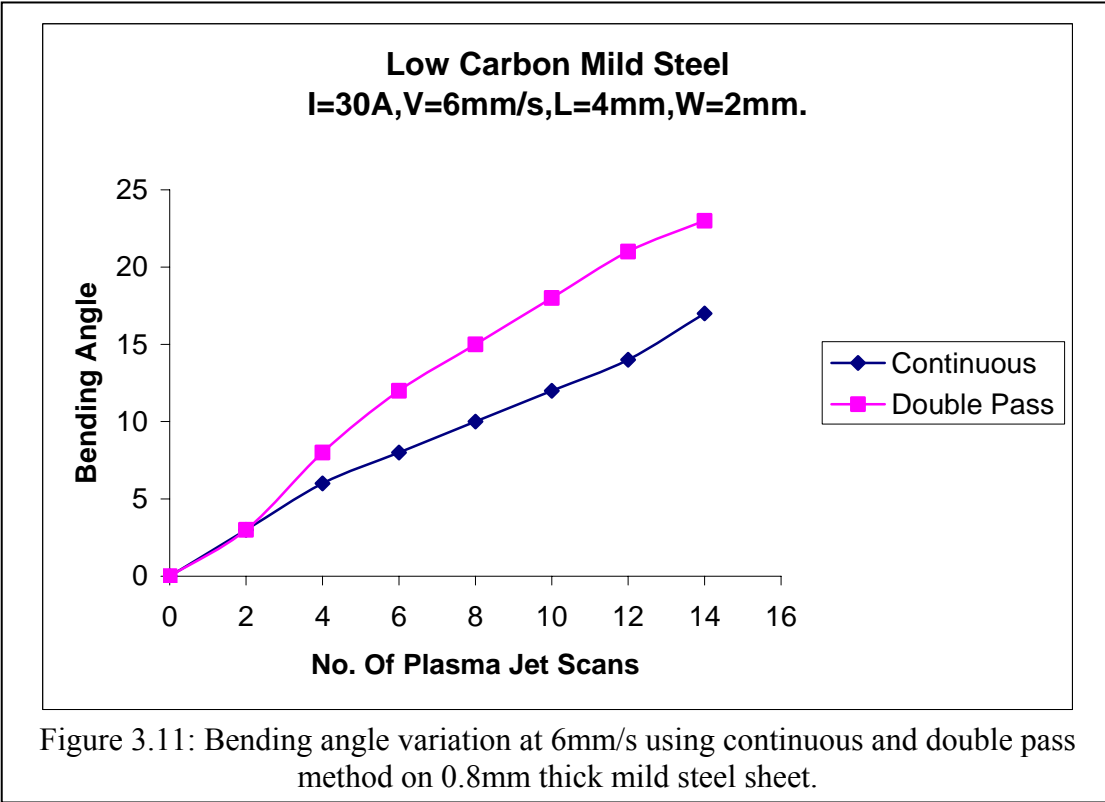
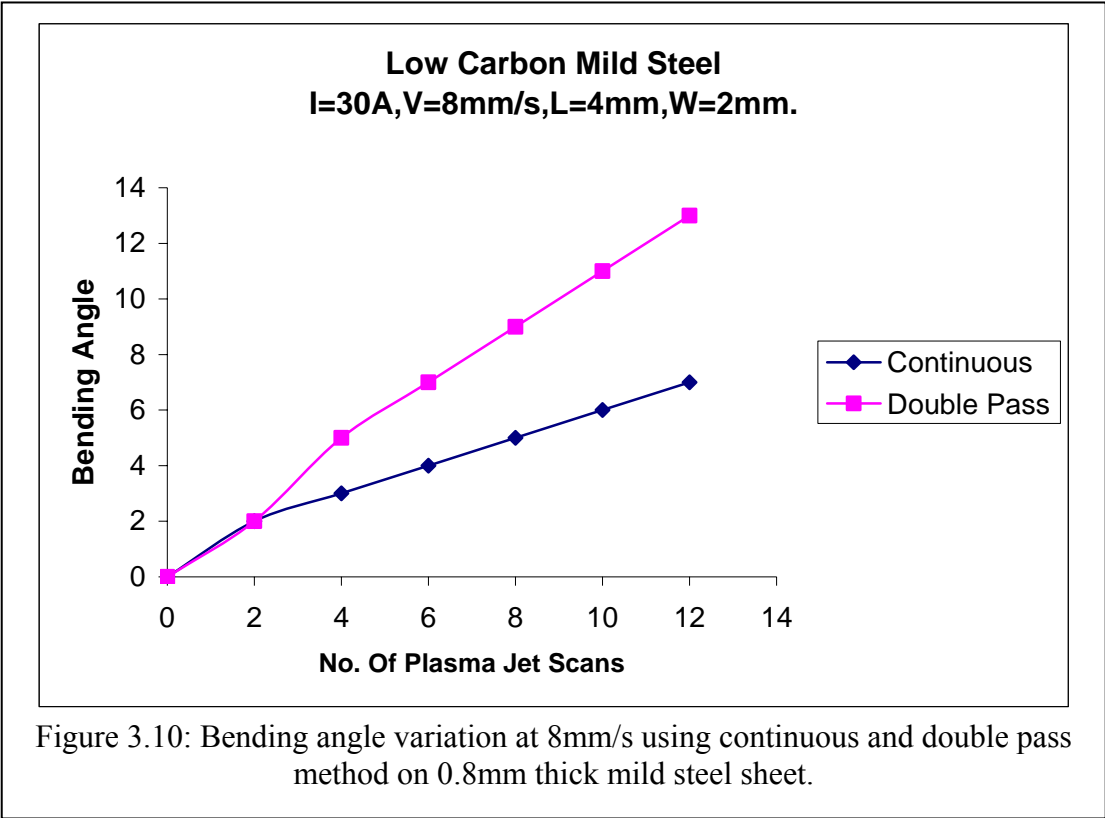
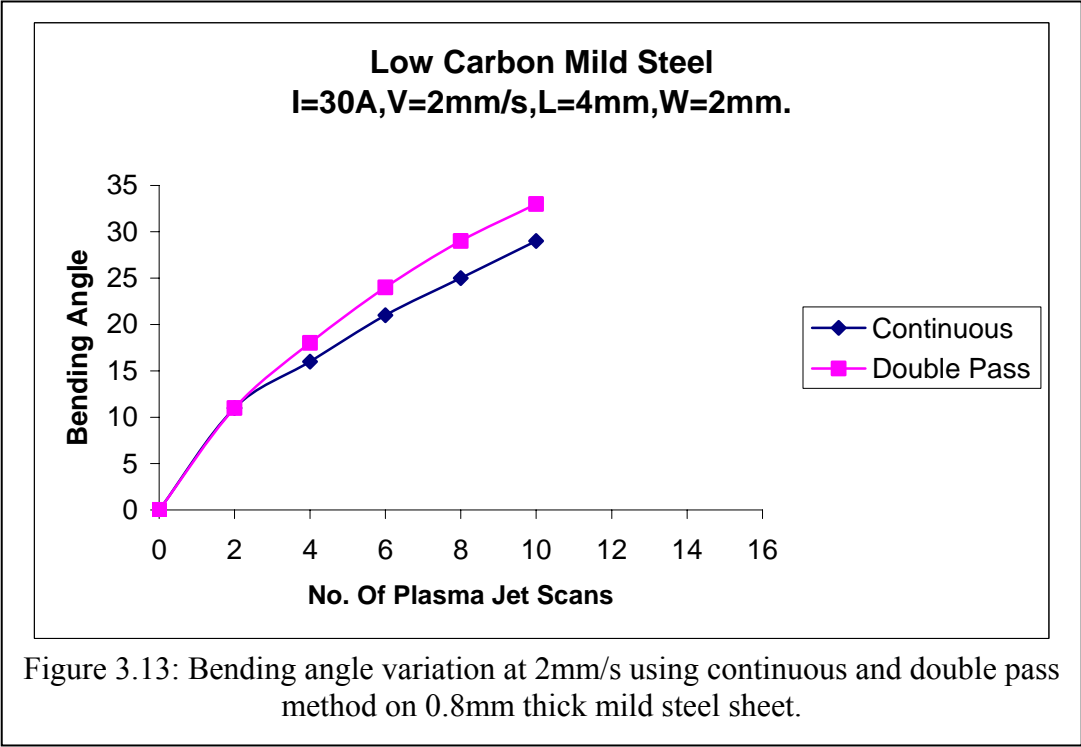
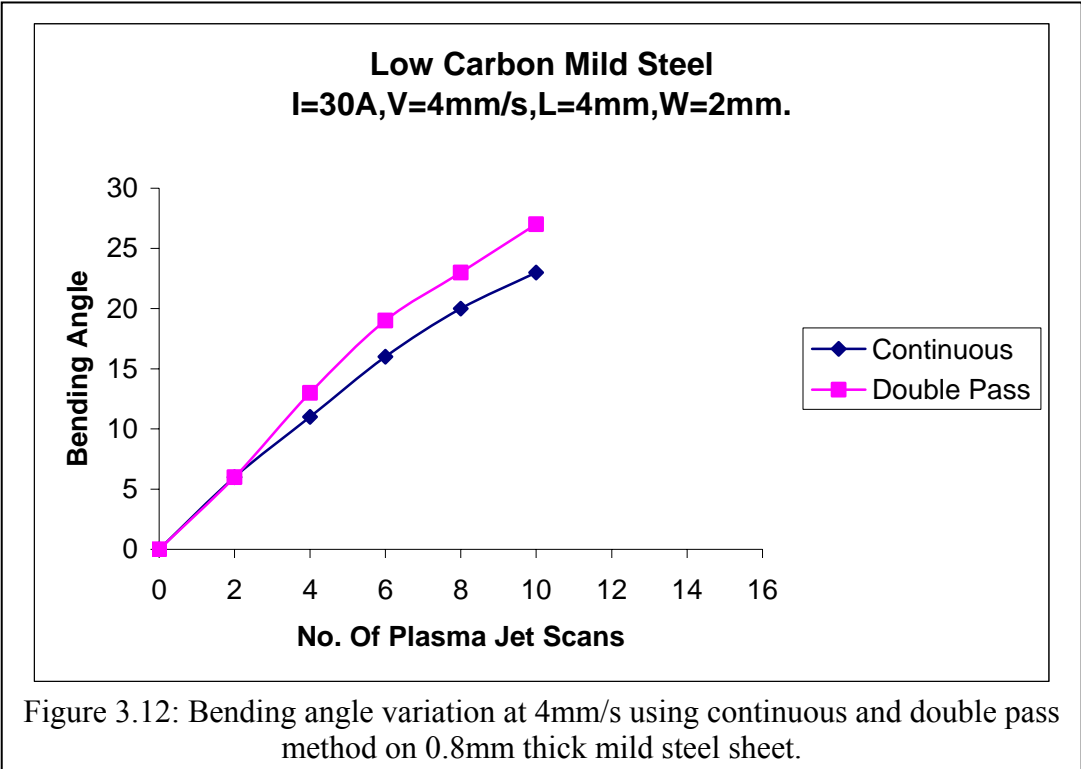
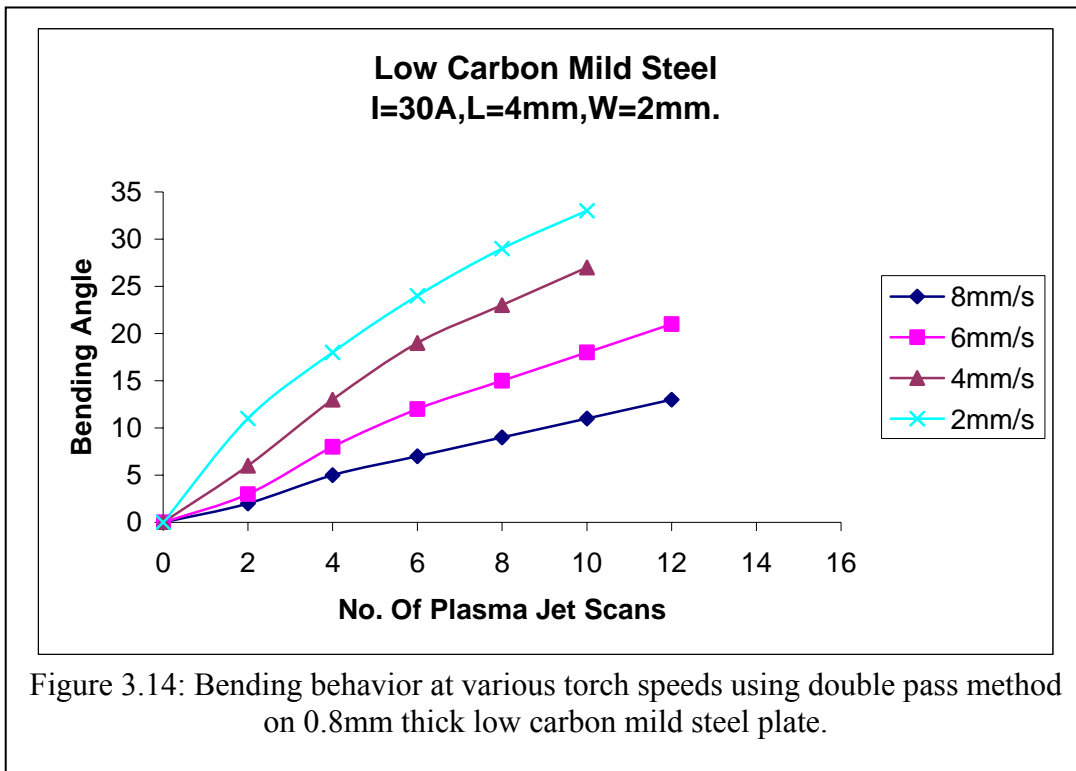


Figure 3.9: Bending angle using double pass method at various forming speeds on 0.8mm thick SS304 sheet.

As observed from experiments (Figure 3.5), a single pass method depicts a similar bending behavior as a continuous pass method. This could probably be because of the time associated with the application of heat in a single pass method. Although alternate heating and cooling takes place, not enough surface temperatures are generated in a single pass method to create a thermal gradient sufficient enough to enunciate significant increase in bending. Using a double pass method a greater rate of bending per pass can be achieved as two plasma scans will not only provide high surface temperatures for temperature gradient between the top and bottom surfaces but also generate stresses that are just enough to provide a larger bend. As the material is cooled, the material properties are retrieved and thus reheating it will lead to generating a thermal gradient equal to that in the previous cycle. This also avoids continuous increase of surface temperatures and subsequent decrease in temperature gradient. The double pass method hence will provide an increased forming efficiency in a low-volume manufacturing environment. Although the processing time increases because of intermittent heating and cooling phenomenon, rapid cooling by using the coolant will help in decreasing the material temperature to ambient conditions faster.





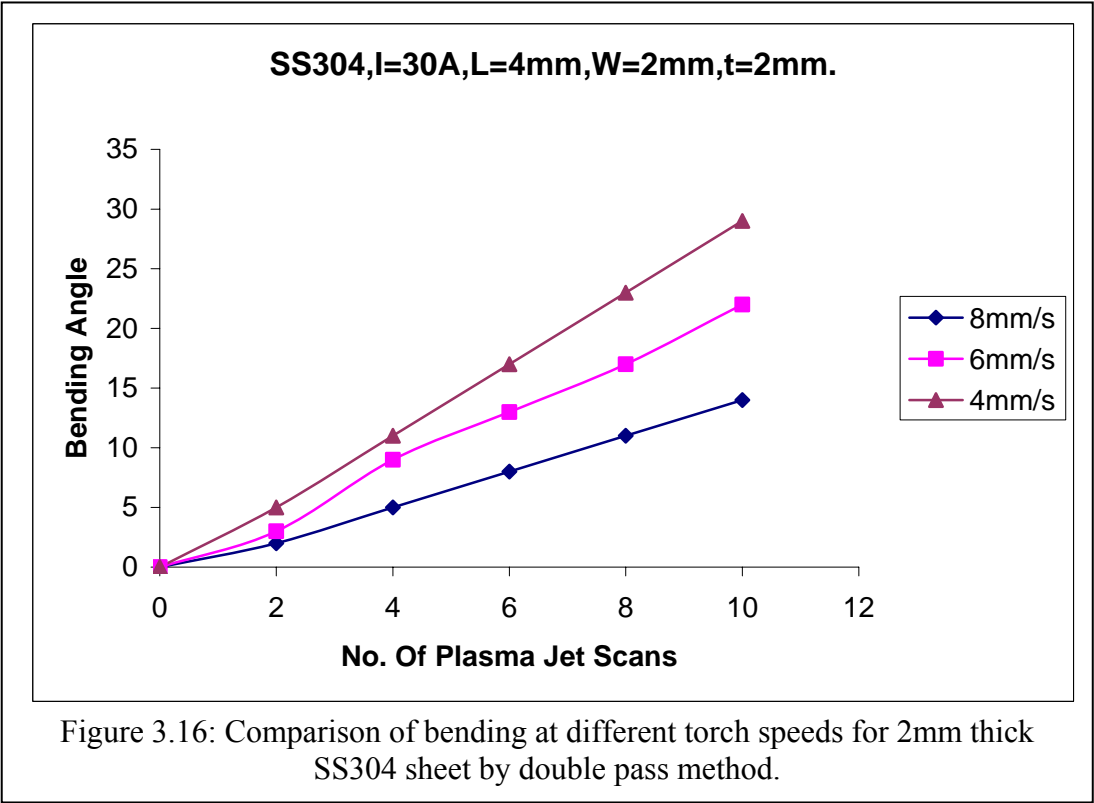
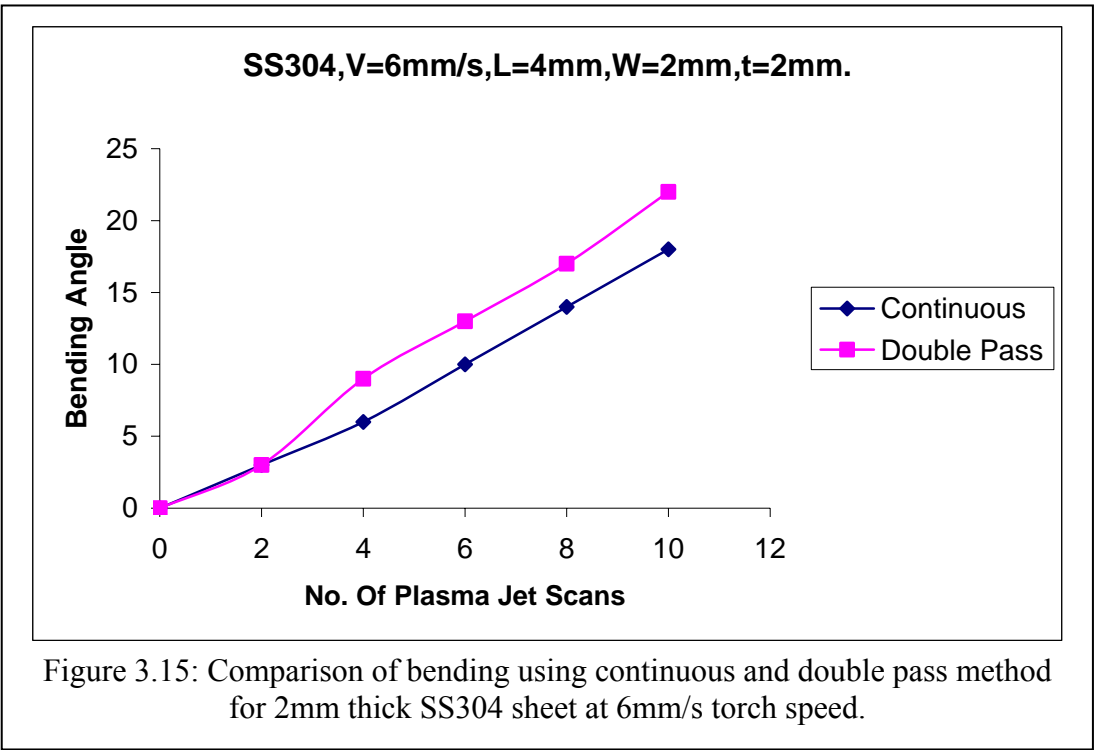


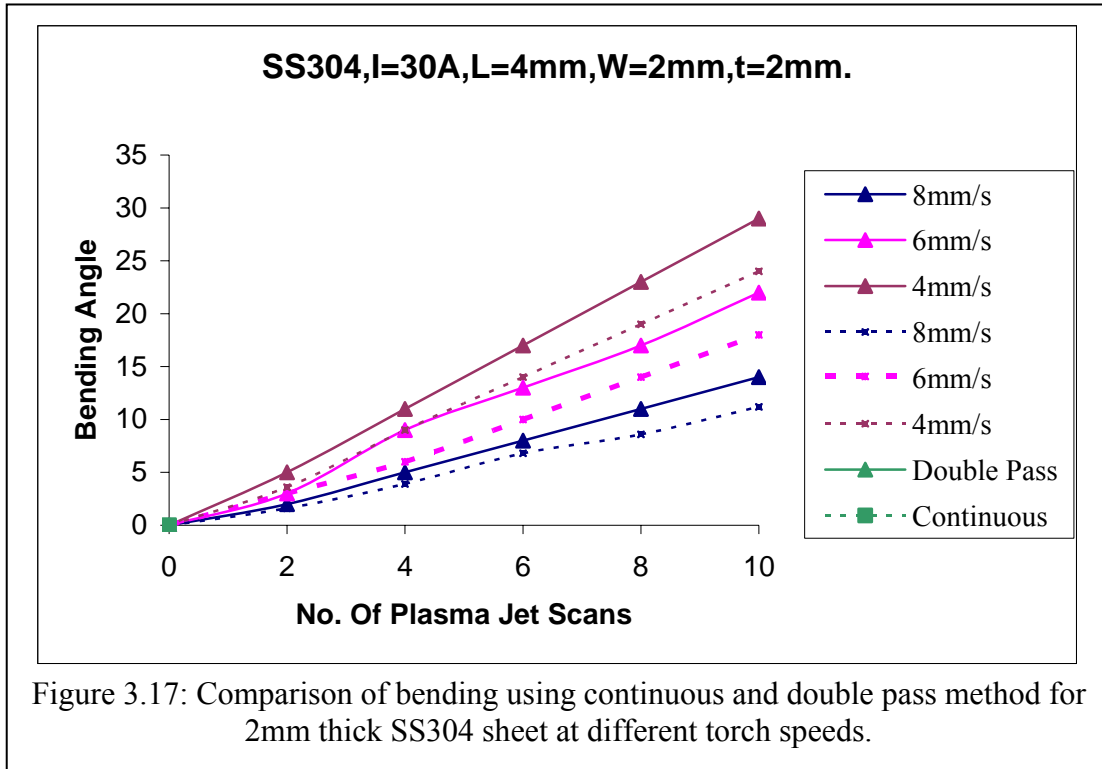
3.4 Effect Of Thickness

The forming parameters such as current and velocity were varied to study their effect of changing thickness on bending. All the experimental observations have been performed on sheets of 0.8mm. SS304 sheets of dimension (130×50×2) mm and (150×50×3) mm are used to determine the effect of thickness on bending.

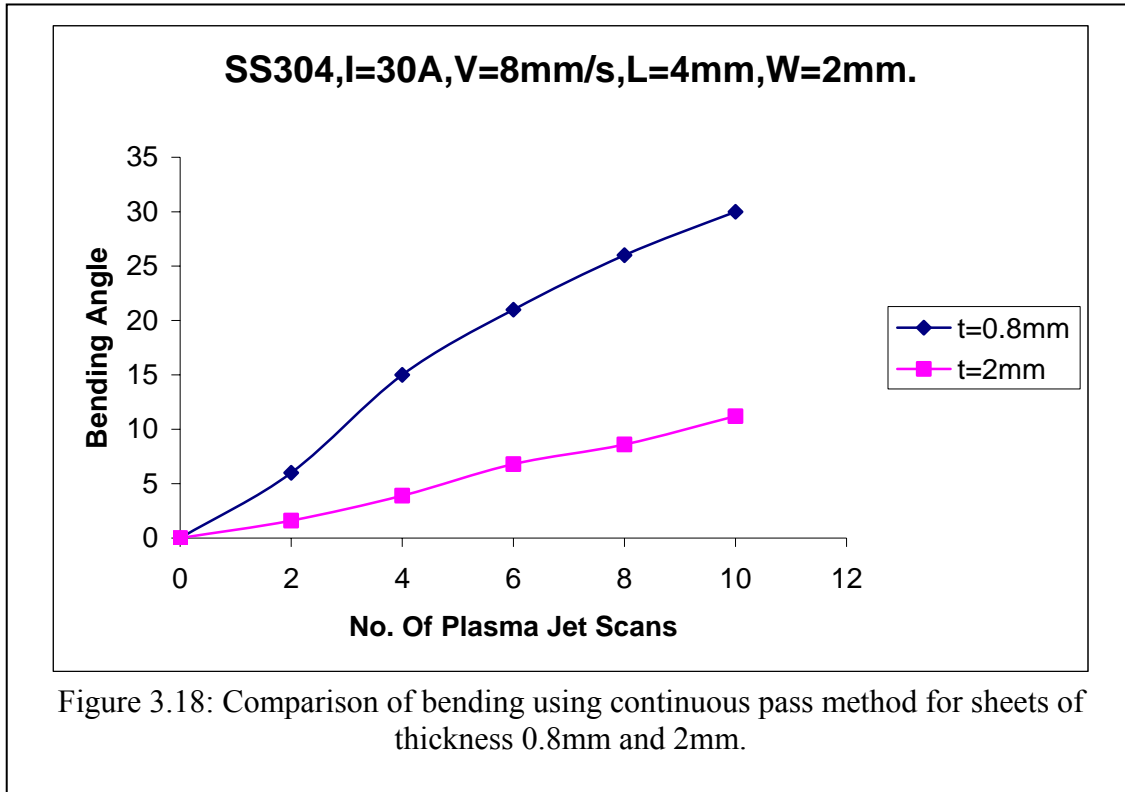
3.4.1 Observations On 2mm Thick Sheets.

Stainless steel sheets of 0.8mm thickness have shown an increase in the bending angle when high power and low torch speeds are used. Typically this is because of high surface temperatures being applied for a longer period of time at low torch speeds. Use of very low speeds (2mm/s) resulted in material damage and local melting of a 0.8mm thickness sheet metal.

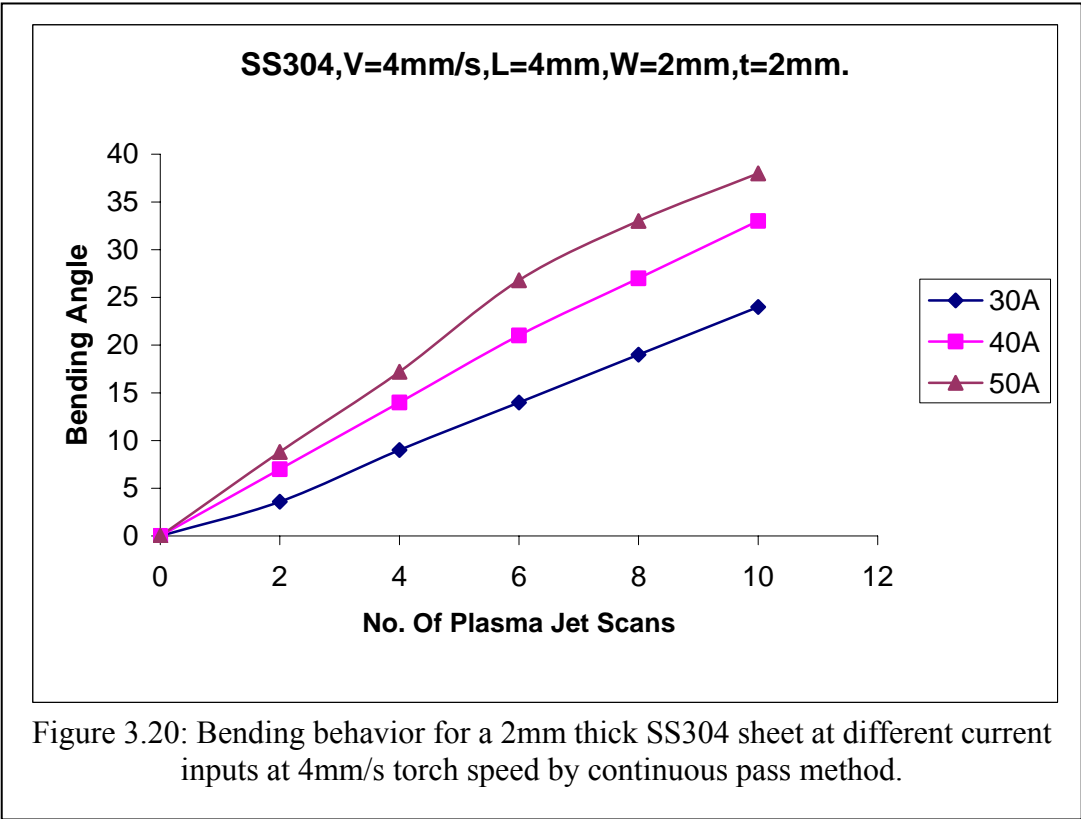
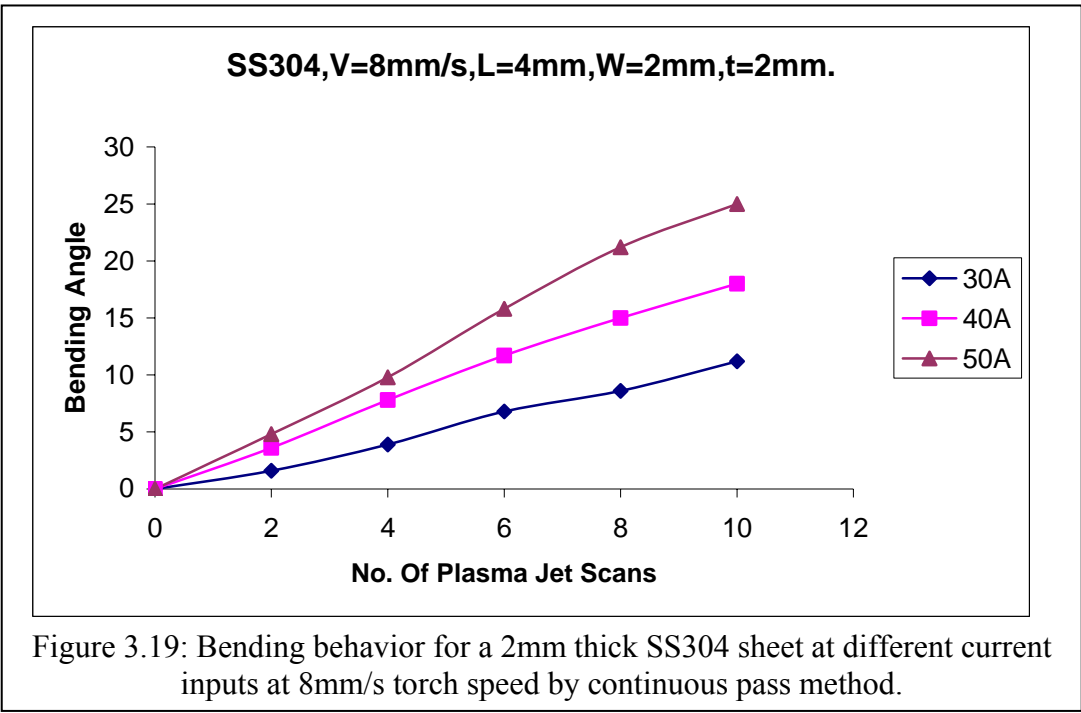




Experiments on the 2mm thick SS304 have been conducted using the standard process parameters, 30A current, 4mm stand-off, and 2mm beam diameter at various torch speeds. The bending angle increased with decrease in torch speed under a constant heat input. Also the deformation in a 2mm thick sheet was found to be less than that observed in a 0.8mm thick metal plate at the same operating parameters. Also, scanning method used for forming has a significant effect on bending of sheets of large thickness. As observed earlier for thin sheets, Use of double pass method has shown significant increase in bending angle for sheets of large thickness than any other scanning method.

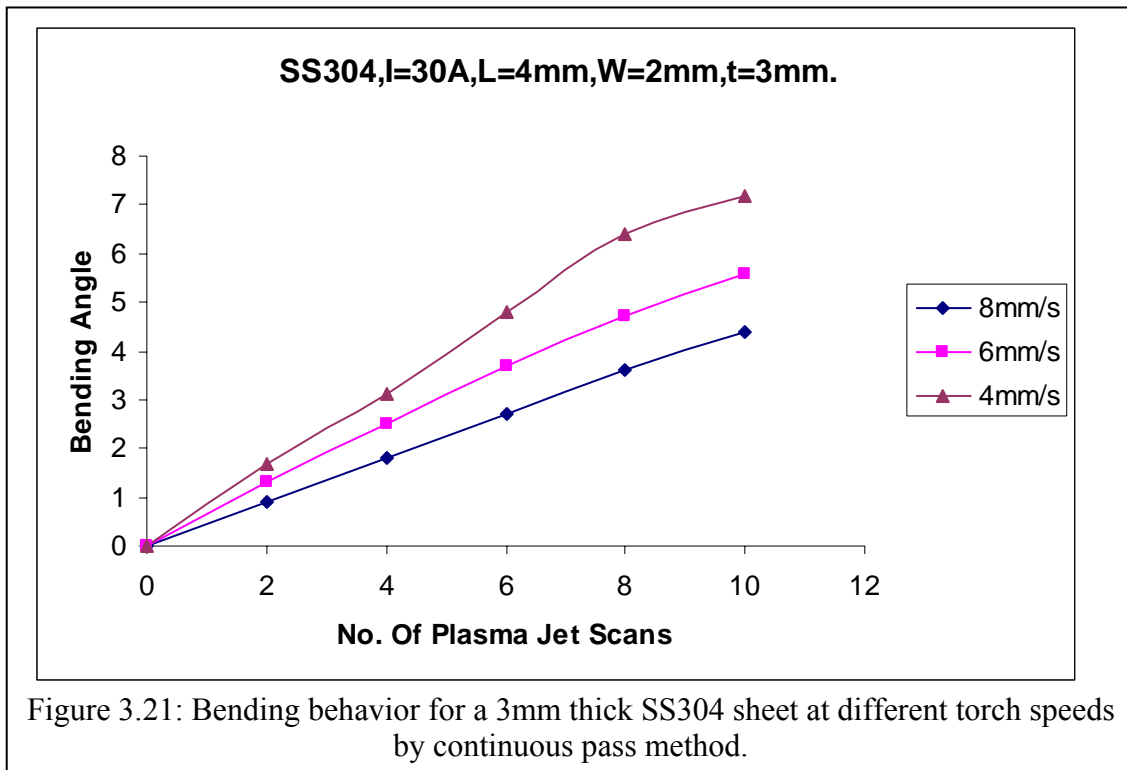


Although a constant heat input rate was used, a decrease in bending with increase in thickness has been observed in the above case. The amount of heat supplied by 30A current may not be sufficient to create larger thermal gradients hence a higher current input was used to study the possible increase in bending. Current inputs of 40A and 50A have been used on sheet of thickness 2mm. Use of these high current inputs resulted in melting of thin sheets, an increase in bending angle has been observed at higher power inputs on thick sheets.



3.4.2 Observations On 3mm Thick Sheets.

To determine the relationship between the forming parameters and their effect on bending with changing thickness, experiments are also performed on a 3mm thick SS304 metal plate. Under a constant heat input, bending behavior decreases with increase in thickness of this sheet. This is mainly due to the need of greater rate of heat input for large cross-sectional areas so that a high temperature difference between the top and bottom surfaces can be created in minimum time.



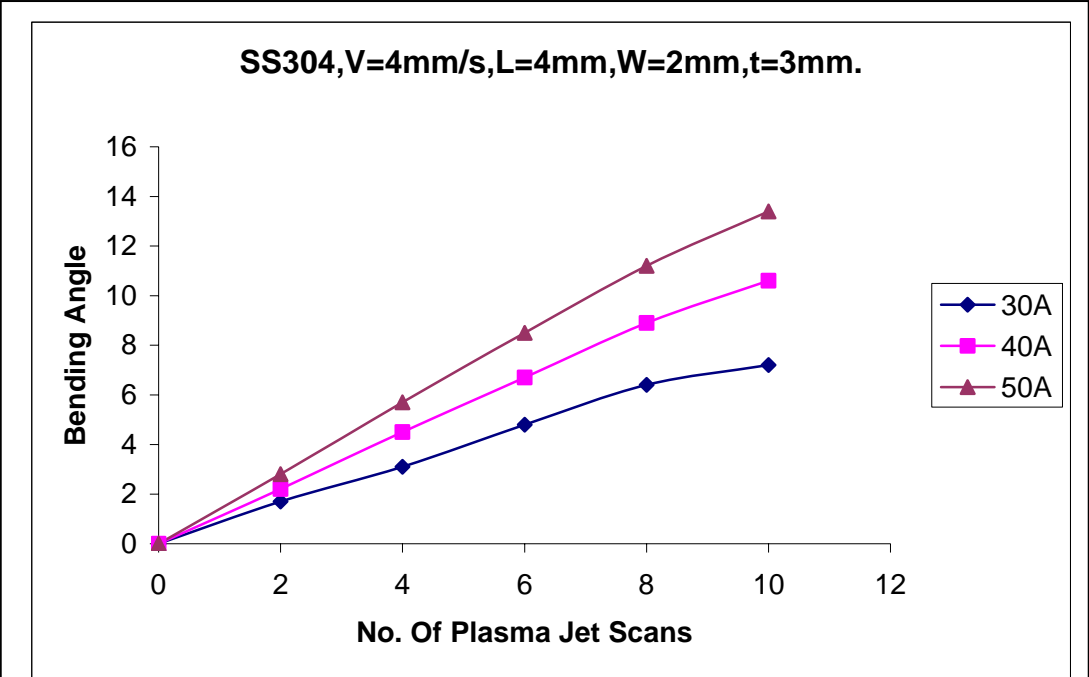


Figure 3.22: Bending behavior for a 3mm thick SS304 sheet at different current inputs at 4mm/s torch speed by continuous pass method.

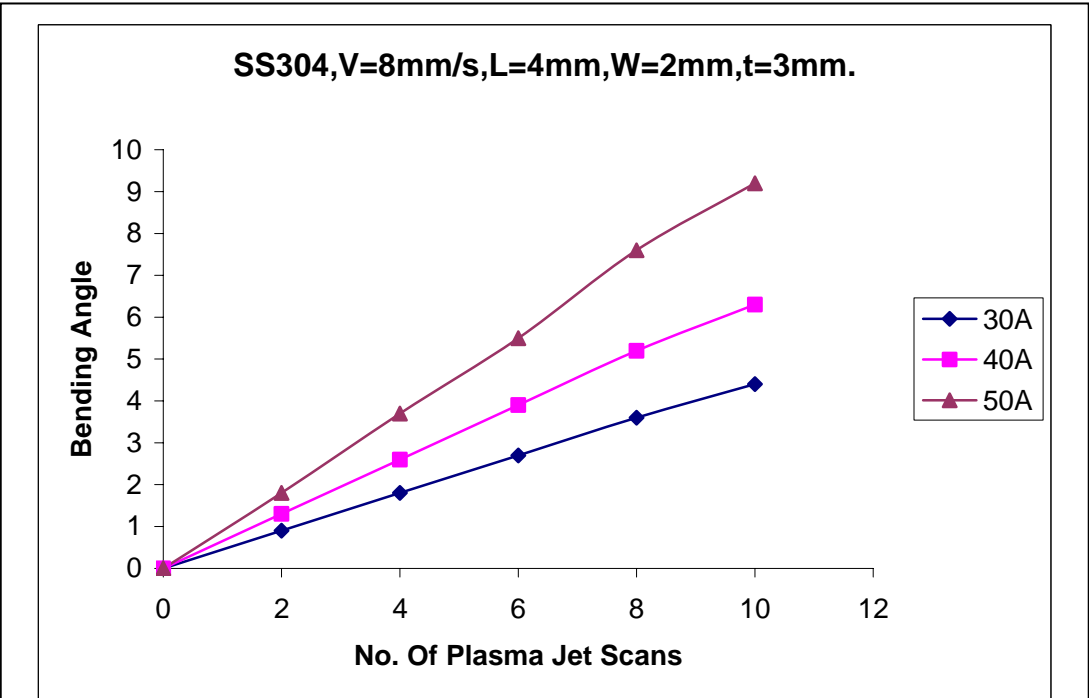
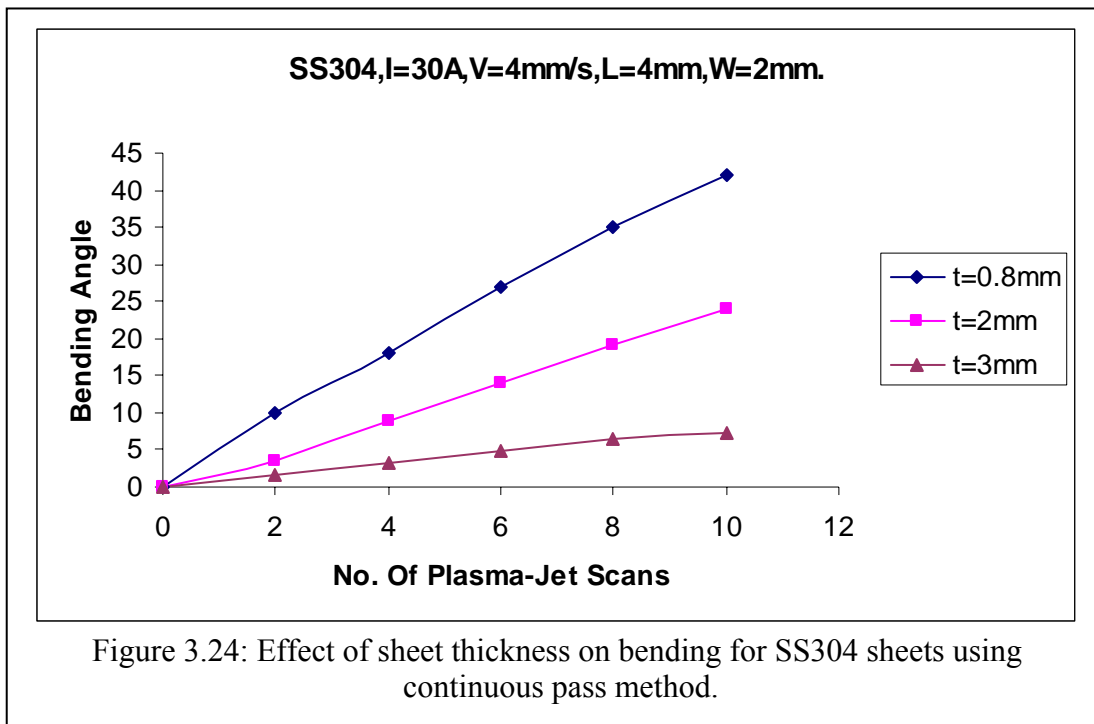


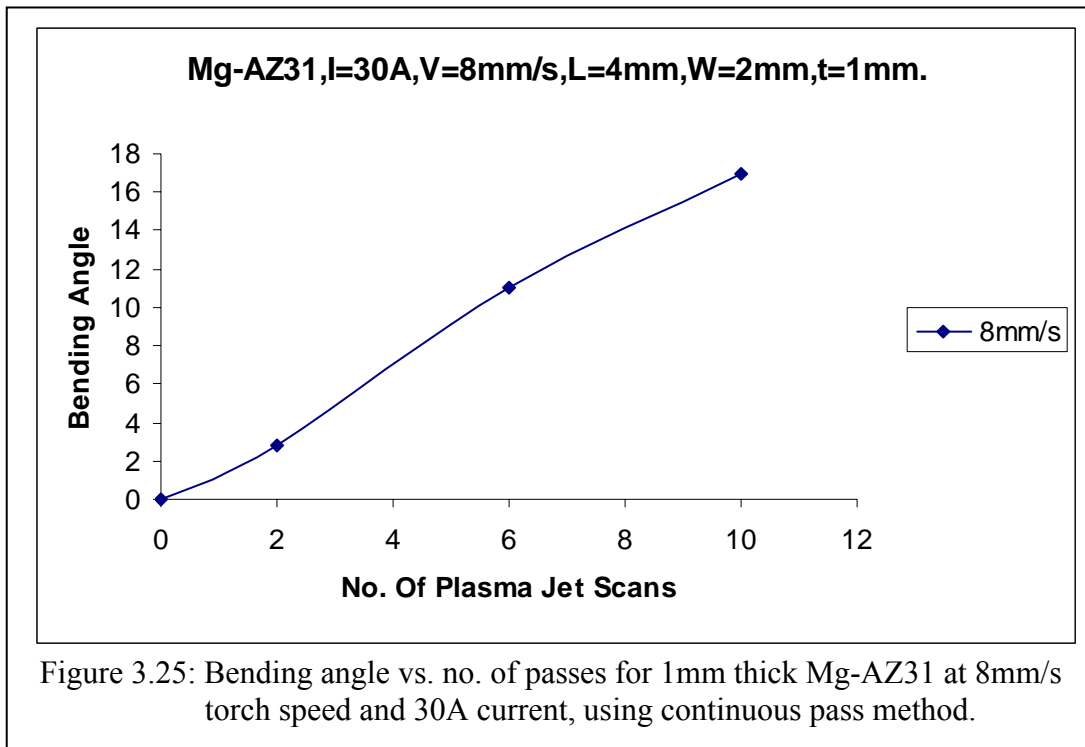
Figure 3.23: Bending behavior for a 3mm thick SS304 sheet at different current inputs at 8mm/s torch speed by continuous pass method.

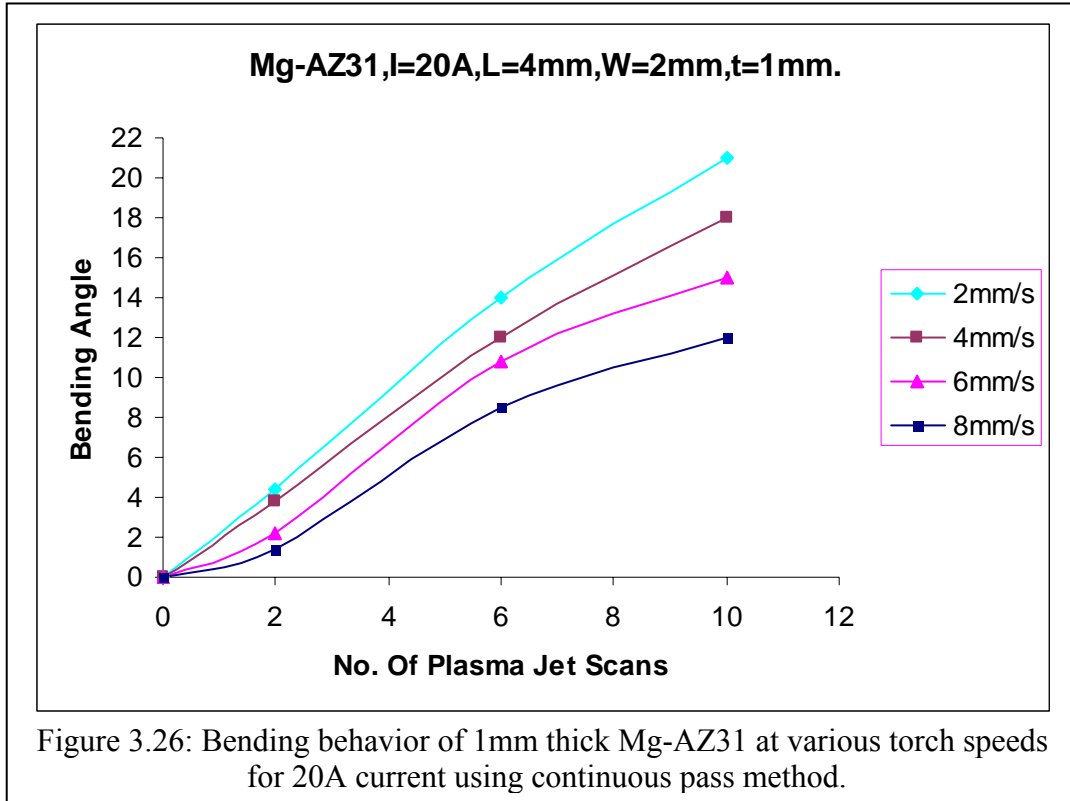
It has been observed that the bending angle is closely related to the heat input as long as the metal surface does not melt. While 0.8mm thick sheets melted at 30A current input, 2mm and 3mm thick sheets could produce significantly large bend angles with 40A and 50A of current. Sheet metals of large thickness needed higher power inputs to produce bending angles almost equal to the thin sheets formed at lower heat inputs. All the experimental observations to study the effect of thickness have been made on SS304 sheets. As the thickness was increased the amount of power input was also increased to obtain bends similar to that of regular thin sheets of 0.8mm. This implies that although sufficiently large thickness is available for the sheet to create a large thermal gradient, greater heat input is needed to generate temperatures high enough for the temperature difference to induce plastic deformation. The experiments on 2mm and 3mm sheets have been conducted using the continuous pass method. Use of a double pass method may increase the forming efficiency and rate of bending per pass further, especially at high heat inputs where a greater thermal gradient is possible. A greater number of passes and high heat inputs are required for sheets of large thickness in a continuous pass method, but then the rate of bending decreases subsequently with increase in the number of passes as the temperature difference between the top and bottom surfaces decreases.



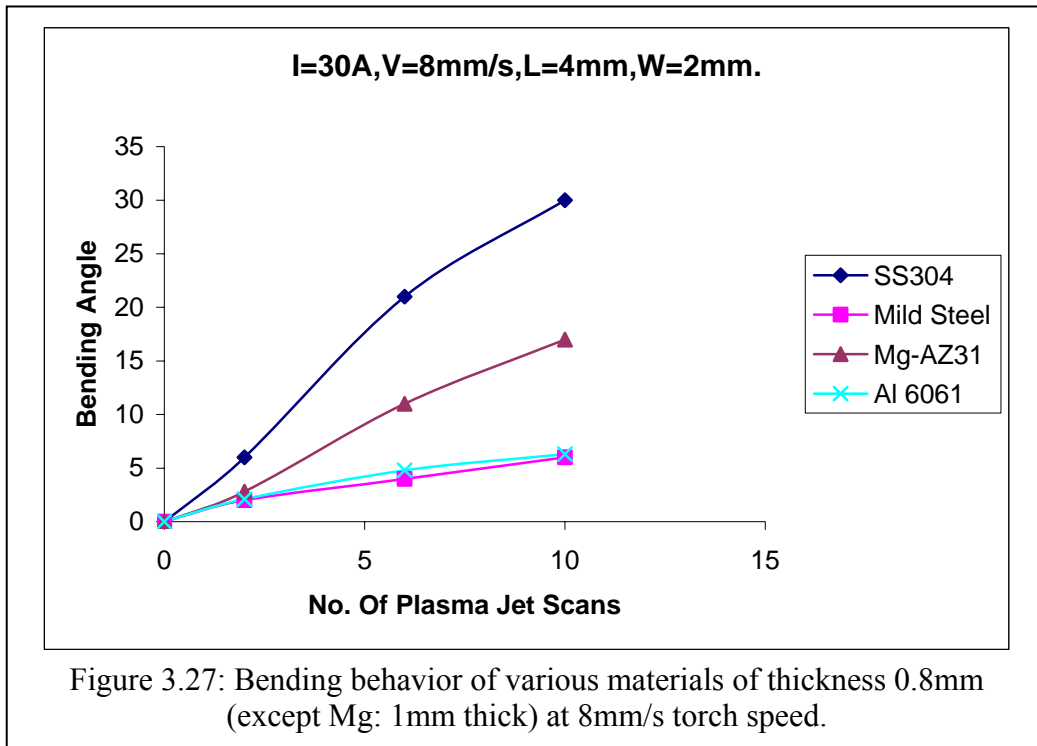
3.5 Plasma-Jet Forming Of Magnesium Alloys

Magnesium and its alloys have found increased applications in today's automotive and aerospace industry. This is mainly because of high strength-to-weight ratio of magnesium alloys. To investigate further, the possible effect of material parameters on bending, thermal bending of magnesium alloys has been considered. AZ31B Mg-Al alloy sheets of dimensions (100×50×1) mm have been used for experiments. The standard forming parameters of 30 Amps current, 4mm stand-off distance, and 2mm beam diameter have been applied. Different torch speeds were used to analyze its effect on bending. Material damage (melting) occurred on the surface of the sheet along the line of heating when 30A current was used at 6mm/s torch speed and below. Hence the current input was later reduced to 20A to study the forming characteristics.





AZ31B has a lower melting point (900K) and relatively higher thermal conductivity when compared to that of the stainless steel, hence it becomes relatively difficult to form at higher heat inputs. While use of a 30A current damaged the material at low and medium torch speeds, lower power input at 20A produced bends up to 22° in 10 continuous passes. Bending angle decreased with increase in torch speed. This was a similar observation of other materials tested earlier.



The figure above illustrates the bending behavior of various metals when similar processing parameters have been used. Use of SS304 sheets resulted in a very high bending values because of low thermal conductivity and high melting point of the material.

3.6 Discussion

Majority of the experiments have been performed using a constant thickness of 0.8mm. A comparison between different scanning options was done to determine an efficient method of forming wherein the material properties are recovered and also the use of resources was considerably reduced. Significant increase of bending angle has been observed using a double pass method when compared to single pass and continuous pass methods. Single pass method and continuous pass methods have shown a similar bending behavior and this can be attributed to less surface temperatures generated during single pass method. In a continuous pass method, the surface temperatures increase eventually with every plasma scan, but the thermal gradient decreases with time as the temperatures gradually pass through the thickness decreasing the temperature difference on the top and bottom surfaces. Also a decrease of bending with increase in passes is observed even though higher temperatures are maintained. This can be attributed to increase in strain hardening in the material along with the decrease in the temperature gradient. A relative increase in bending in a double pass method is mainly because of a constant thermal gradient being maintained whenever heating is restarted. The material is allowed to cool down after every two plasma scans. Reheating the material will allow the metal to reach the same maximum surface temperatures as in previous passes and in turn maintain the thermal difference along the thickness. Also any residual temperatures left in the sheet will help in increasing bending as the flow stress is considerably reduced. The double pass method is also effective especially on mild steel. Alternate heating and cooling will allow materials of high thermal conductivity to maintain consistent gradient. The major increase in bending using a double pass method is mainly observed after the second pass, when reheating from ambient temperature occurs. This increase in bending is observed even in subsequent passes until strain hardening, section thickening and other thermal effects hinder the increase in bending further.

As the thickness increases, it has been observed that rate of bending decreases, when the same heat input parameters are used. For materials of greater thickness, increase in the heat input by increase of current led to greater bends. As the cross-sectional thickness of the sheet increases, rapid heating is required to reach peak temperatures. Although there is enough thickness available to create a temperature gradient, the normal heat inputs used for thin sections will not be sufficient to generate high surface temperatures required for creating stresses that lead to

deformation of the metal plate. Also the thermal stresses developed will not have created high plastic strains required for large deformations.

It has been observed that while a 0.8mm sheet melts at lower speeds when a 30A current is used, 2mm and 3mm thick sheets can sustain high heat inputs provided by 30A and 40A current inputs and also provide large bending angles than at lower heat inputs. As shown in Figure 3.22 and 3.23, bending rate can be rapidly increased with the use of large heat inputs for thick sections until no material damage is incurred.

Magnesium AZ31B alloy of thickness 1mm is used for experimentation using plasma-jet forming. It has been found that material damage occurs when a 30A current and low torch speeds are used on AZ31. Al6061 and AZ31 have similar melting points of about 900K. No material damage occurred at higher heat inputs on Al6061. This is presumably because of higher thermal conductivity of aluminum alloys. Magnesium alloys have low thermal conductivity (77 W/mK) and hence when lower torch speeds are used, very high surface temperatures are generated.

When smaller input currents are used on magnesium alloys, large bending angles have been determined. It is also observed that larger bending angle was obtained with an AZ31 sheet when compared with low carbon mild steel. Mild steel has lower thermal conductivity than magnesium alloys and hence a greater bending is expected especially in thermal forming applications. This increased bending in AZ31 could probably be because of the use of fine grained material. A fine grained structure will enable the material to soften easily and hence improve formability of the sheet. This can be determined only when metallurgical studies regarding the effect of grain structure are performed.

As the number of passes increased, the rate of bending decreased. This behavior is observed in all the materials formed using plasma-jet forming. The reduction in bending in a multi pass line heating method as the number of passes increases may occur if hardness of the material increases with every pass. Strain hardening occurs whenever entanglement of dislocations in the atomic structure happens due to plastic deformation. As the entanglement of dislocations increase, deformation decreases and hardening increases [25]. Surface temperature variations also lead to either increase or decrease in bending as the number of passes increase. While any inherent temperature in the material reduces the flow stress to increase formability, there are equal chances of reduction of temperature gradient between the top and bottom surfaces. Bending hence decreases rapidly as the number of passes increase for materials of high thermal

conductivity, use of intermittent passes will be beneficial for these materials than that of continuous passes. Although the process time increases with the use of alternate heating and cooling methods, rapid cooling jets will help reduce process time by significant margin.

Surface temperatures determine the overall temperature difference to be generated between the top and bottom surface. Hence for plasma-jet forming to be fast and efficient, determining an optimum peak temperature that will enhance the bending capability by providing larger thermal gradients is necessary. A temperature field analysis coupled by a structural analysis will help in investigating the effects of physical and mechanical properties of materials on bending both at lower and elevated temperatures. The study of the stress distribution will allow further improvements in the process. Also the effect of surface temperatures and thermal gradient in sheets of different thickness formed using continuous and double pass methods can be compared. To investigate the above, a finite element thermo-mechanical simulation has been performed. The effect of temperature field distribution and the plastic strains on thermal bending using the results from a computational model will be discussed in the next chapter.

CHAPTER IV

THERMO-MECHANICAL SIMULATION USING ANSYS

4.1 Background

Numerical simulation is generally performed using advanced finite element programs. The finite element method (FEM) is a discrete procedure for complex continuum problems that demand tedious computations supported by mathematically defined statements. FEM is an active investigation tool that is highly beneficial in numerical analysis and problems that involve transient dynamic analysis of varied disciplines such as structural analysis, heat transfer, fluid flow and electro-magnetic simulations. FEM programs not only reduce the computational time but also help in solving very complex problems to an optimum value eliminating the need of equation formulation and manual calculations.

Numerical simulation of a plasma-jet forming process will involve a nonlinear coupled transient thermo-mechanical simulation. The thermal modeling is used to determine the transient temperature field analysis on the sheet metal resulting from the heat flux generated by a moving plasma heat source. The temperature effects of the moving heat source are transferred to a nonlinear transient structural analysis model to predict the stresses and large deformations that occur in the metal plate. Finite element modeling of plasma-jet forming will involve large nonlinear inelastic deformations. Modeling and analysis of these complex computational cases will require a finite element program to be typically incremental and iterative. Hence a commercial general purpose finite element computer program ANSYS10.0 [35] will be used for analysis of plasma-jet forming.

4.2 Computational Modeling Of Plasma-Jet Forming

Thermo-mechanical simulation of plasma-jet forming is a two-step process. The initial step involves nonlinear transient spatial distribution of the heat flux induced by the non-transferred plasma torch to determine the temperature field distribution on the surface of the sheet material. Once the time dependent temperature field analysis is completed, these temperatures are applied at various nodes on the material to assess the stress-strain behavior and consequent effects of plastic deformation of the material. In the thermo-mechanical analysis, an incremental theory of plasticity is generally applied. The plastic deformation of material should satisfy Von Mises yield criterion and the corresponding flow rules associated with the material behavior [36].

The heat generated at the tip of the plasma torch is passed by the plasma-jet to the top surface of the metal plate based on the Fourier's law of heat conduction. The plasma torch moves over the sheet metal in the x-direction with a velocity v_x . The general heat transfer equation in this case for the metal plate is:

$$\rho c \left(\frac{\partial T}{\partial t} + v_x \frac{\partial T}{\partial x} \right) = \frac{\partial}{\partial x} \left(k_x \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(k_y \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left(k_z \frac{\partial T}{\partial z} \right) \quad (1)$$

T is the temperature, c is the heat capacity, ρ is the density and k_x , k_y and k_z represent the thermal conductivities of the material. The workpiece has been considered to have isotropic material properties. Thermal properties of the material such as thermal conductivity, specific heat, density and enthalpy are temperature dependent. Same value of thermal conductivity is used in all the three directions. The conduction and convection coefficients on the surface of the metal plate have a major role in determining the temperature field behavior during plasma-jet forming. While the simulations of a 3-D solid model for plasma-jet forming using FEM is highly time consuming, reduction of the computational time can be obtained by specifying a pre-defined temperature for material properties. In plasma-jet forming, the material is heated to temperatures that do not exceed the melting point of the sheet material used. The initial temperatures are set to the ambient conditions of the material before being formed. The heat induced by a plasma beam at a particular spatial coordinate follows the Gaussian distribution characteristics.

The concepts for determining thermal history on surfaces for thin and thick sheets with moving heat sources are based on Rosenthal's theory for generalized equations on heat flow. The key to Rosenthal's solutions are some major assumptions such as existence of a quasi-stationary

temperature distribution. The heat source is also considered to be a point heat source that moved with a constant velocity along the x-axis of a fixed rectangular coordinate system [38]. Based on these assumptions, a typical temperature distribution around a moving point heat source is given as:

$$\frac{\partial^2 T}{\partial \xi^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} = -\frac{C\rho}{k} v \frac{\partial T}{\partial \xi} \quad (2)$$

ξ is defined as the distance of the point heat source from a fixed reference point on the x-axis and is give by :

$$\xi = x - vt \quad (3)$$

Rosenthal further solved eq.2 to obtain a simplified heat flow equation for both thin and thick plates applicable to two dimensional and three dimensional heat flow conditions:

$$T - T_o = \frac{q}{2\pi k} e^{v\xi/2\alpha} K_o \frac{vR}{2\alpha} \quad (4)$$

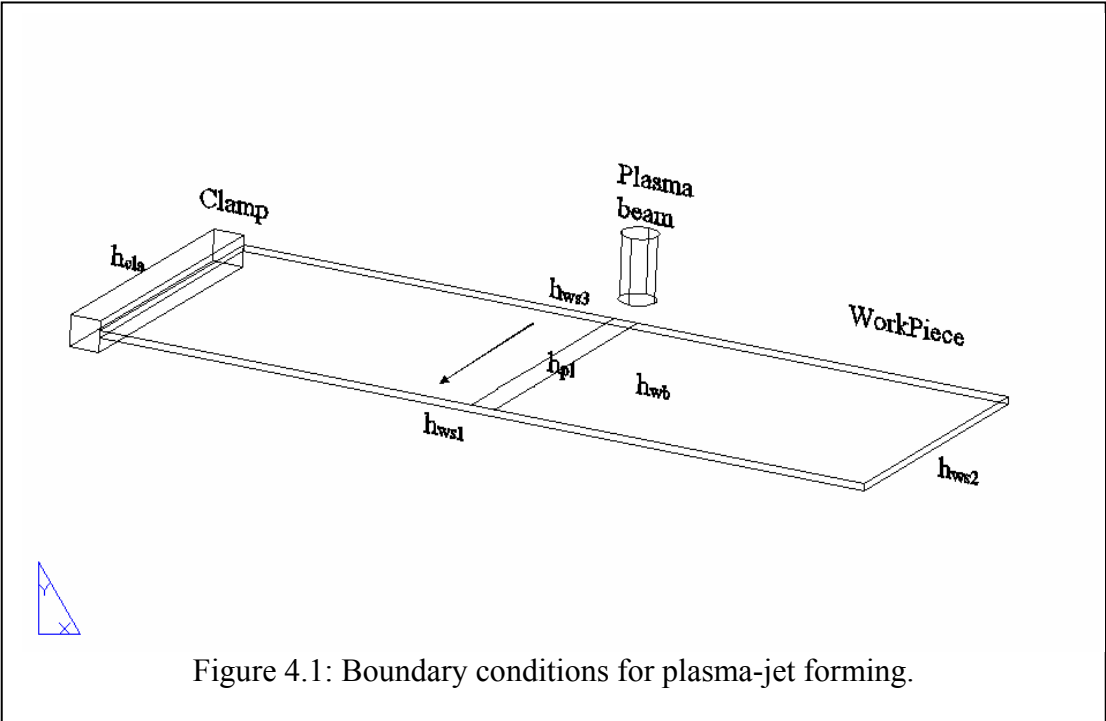
Rosenthal's model is an infinite series solution to the heat dissipated by conduction in a semi-infinite work piece with constant thermo physical properties [38]. While numerous advancements of this model exist, the above equations formed a basis for time-temperature distribution around a heat affected zone because of a moving point heat source. Various numerical modeling programs have been developed based on Rosenthal's generalized heat flow equations with vast applications in welding and hot working. Validations of the time-temperature relations obtained from analytical approach with that of experimental results will help in further optimizing the line heating approach for plasma-jet forming.

The input plasma heat or energy on the surface of the sheet metal is given by [26]:

$$q = \frac{f \cdot E \cdot I}{W \cdot V} \quad (5)$$

q denotes the input energy per unit area and f represents the heat transfer coefficient for a non transferred plasma jet. Plasma generally has higher heat transfer efficiency and source intensity than the lasers. The heat source intensity of plasma is generally between 5×10^6 and 5×10^{10} W/m² and the heat transfer efficiency is usually 80% to 90% [37]. After the temperature

distribution is analyzed using the thermal/heat transfer analysis, the temperatures are applied with the predefined boundary conditions to predict any possible deformation and eventually study the stress distribution along the plate. The boundary conditions for plasma-jet forming represent the actual experimental position of the metal plate while being formed. The ambient temperatures along with convective boundaries are used as initial and boundary conditions in thermal analysis (Figure 4.1). The clamping of sheet on one end is used as the boundary condition in mechanical/structural analysis. With the applied boundary conditions and temperatures on the metal plate, the metal plate will undergo inelastic (plastic) deformation. Due to the temperature differential along the x, y and z axes, thermal strains will develop varying with time. These in turn will give rise to bending moments causing the plate to deform.



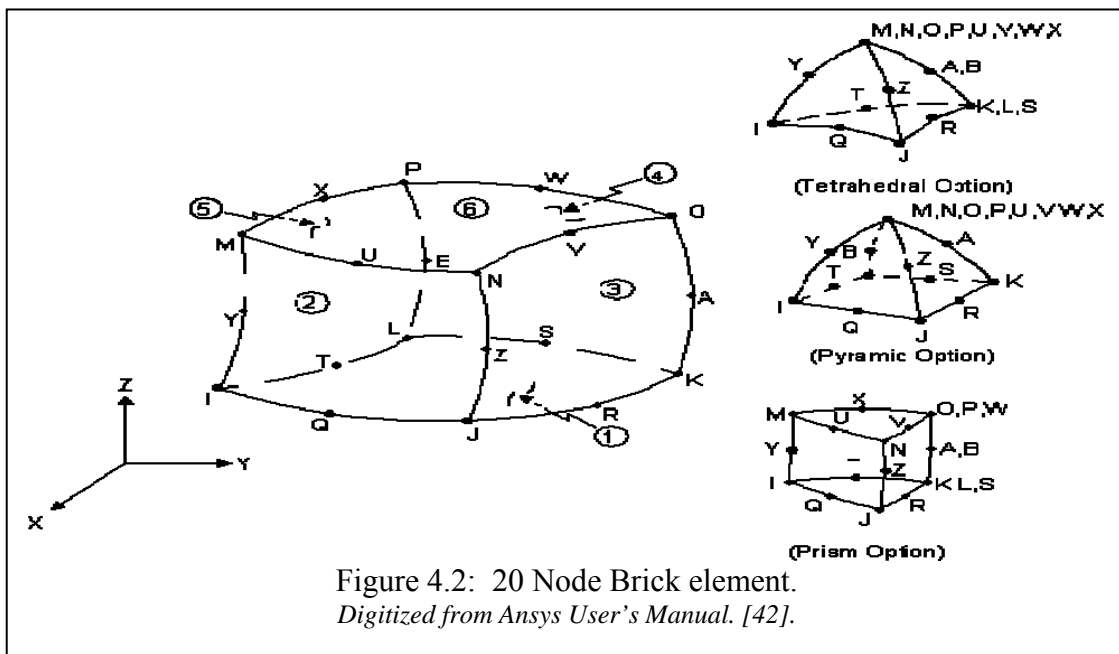
Nonlinear material properties are required for an inelastic structural analysis. Also a constitutive material model is fundamental for a finite element simulation of plasma-jet forming. The material constitutive models for cyclic loading prove to be more complex than those of monotonic loading. In FEM, relationship between stress-strain(σ - ϵ) curve for the specimen being formed will mainly determine the final bending behavior. The stresses and strains resulting from the temperature difference created in the metal plate will be constructed into the σ - ϵ curve to

determine whether the thermal loading has resulted in an inelastic or plastic behavior. While nonlinear elastic modulus is used for these simulations, yield point of the material after each thermal cycle will have a major effect on the final deformation of the sheet metal in plasma-jet forming. The material modeling plays a crucial role in obtaining accurate results in thermo-mechanical simulations. The model must not only account for varying strain, strain rate and temperature but also the changing microstructure. The latter is a function of the previous thermo-mechanical history of the material. Micro-structural behavior is a major criterion in thermal forming simulations especially for stainless and low carbon steels that undergo these changes at temperatures much below their melting points. Interpretation and validation of results obtained at the end of structural analysis is another important aspect in FEM.

4.3 Numerical Simulation Using ANSYS

Numerical simulation using any commercial finite element code will require determination of a sequential algorithm that can be executed to perform the analysis. A coupled nonlinear transient thermal-structural analysis is required for plasma-jet forming. The main focus being the interaction between temperature field and the deformation of the sheet based on the thermal stresses developed by plasma irradiations on the sheet metal.

Discretizing the element type into number of finite element divisions of the appropriate element type is the first major step. Selection of element type is highly dependent on the nature of analysis being pursued. A 20 node brick element is used for 3-D coupled field analysis of plasma-jet forming (Figure 4.2). The decision of using this element was based on need for an element type suitable for coupled-field analysis and sustain the system size constrains for computations. A 20 node brick element has compatible temperature shapes suitable for 3-D transient thermal analysis that can be switched over to study the results corresponding transient structural analysis.



The nature of heat flux distribution on the surface because of a moving heat source has been assumed to be uniform and the Gaussian heat flux distribution is neglected. This was mainly done to decrease the complexity of the program and overall computation time. The materials used in this analysis are isotropic and continuous. The plastic deformation generates no internal

energy as the heat generated during plastic deformation is small when compared to the energy input in the plasma-jet forming and hence is negligible. The temperatures induced by the heat flux onto the surface are below the melting point of the metal and hence no melting takes place. Sequentially coupled thermal and structural analyses have been implemented and are performed separately. While the radiation distribution is generally nonlinear, in this analysis the effects of radiation have not been considered. The convection coefficients along the boundaries have been increased to nullify the effect of radiation. The total strain is considered to be sum of elastic and plastic strains. The plastic strain values will be predominantly high when compared to elastic strain values. Also, no external load is assumed to be applied on the workpiece. The sheet metal is clamped on one edge in the plasma-jet forming process.

The material model has to be accurate for both nonlinear thermal and structural analysis to be optimum. While temperature dependent thermal properties are required to determine the temperature distribution, temperature dependent physical properties and a nonlinear σ - ϵ curve that satisfies the kinematic hardening model determine the amount of inelastic deformation and stresses induced in the model. All the simulation work done illustrated in this dissertation is on a SS304 metal plate of dimension (130×50×0.8) mm for torch speeds from 2mm/s to 10mm/s. The tables below illustrate the composition of SS304 and nonlinear thermal properties for SS304.

Table 4.1: Chemical composition of SS304 by percentage (%).

Alloying Elements	Percentage(by weight)
Cr	18.1
Ni	8.4
Mn	1.6
C	0.1
Si	0.69
P	0.04
S	0.022
Mo	0.31
Cu	0.33
V	0.48
Fe	69.93

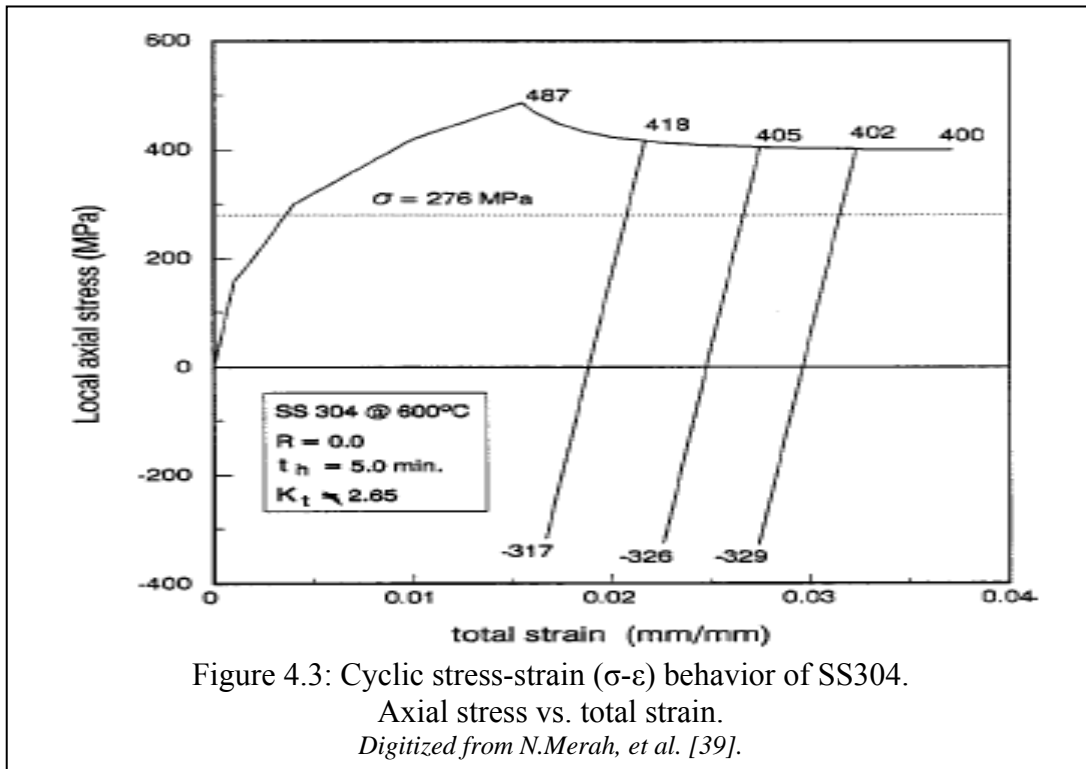
Table 4.2: Temperature dependent thermal properties of SS304 [39].

Temperature (K)	Density (Kg/m³)	Thermal Conductivity (W/mK)	Specific Heat (KJ/Kg K)
300	7900	16.5	495
500	7850	17.5	532
1000	7600	23.3	595
1500	7340	31.0	660
1700	7200	34.4	690

The material properties above in table 4.2 are vital in terms of the temperature field distribution that determines the stress-strain distribution and corresponding inelastic deformation on the surface.

Table 4.3: Temperature dependent mechanical properties of SS304 at room temperature and 900K [39].

Temperature (K)	σ_y (Mpa)	σ_u (Mpa)	E (Mpa)	n
300	291	606	189000	0.105
900	137	369	148000	0.15



FEA simulations using ANSYS for nonlinear behavior of materials models for inelastic deformations using σ - ϵ curves can follow multilinear isotropic and multilinear kinematic hardening options. A nonlinear kinematic hardening model is used in this simulation.

While the yield stress criterion determines the rate of deformation, change in flow stress with increase in temperature and strain rate are also vital for plasma-jet forming where large plastic deformations are prevalent. Accuracy of the material model used so as to fit the exact σ - ϵ curve similar to experimental parameters is of greater significance for determination of the stress distribution in structural analysis.

The geometric model used for numerical studies is similar to that of the metal specimen used for experiments. The mesh model has been divided such that it is finest along the heating zone where the thermal gradient is maximum and temperature changes are rapid. As a 20 Node brick element is used for 3-D analysis (Figure 4.2), Solid90 element is used in thermal analysis and is automatically converted to solid95 in structural analysis. This helps in maintaining the same geometrical and mesh model for both thermal and structural analysis.

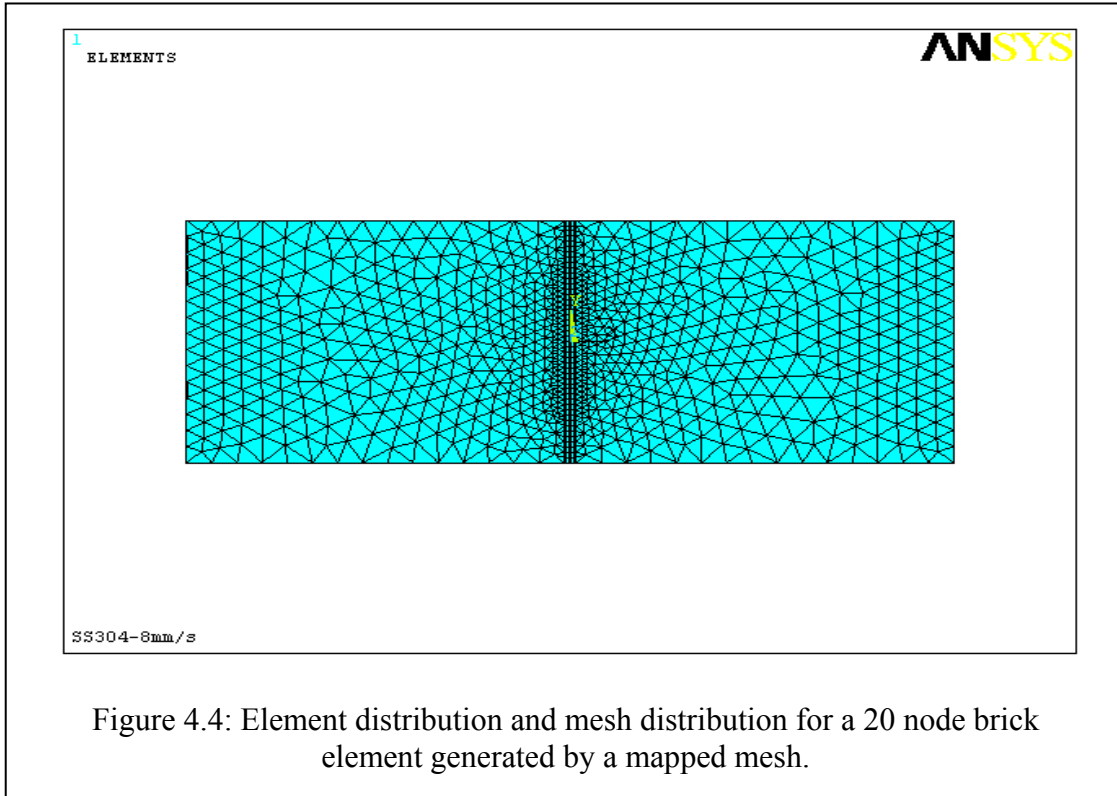


Figure 4.4: Element distribution and mesh distribution for a 20 node brick element generated by a mapped mesh.

The finer the mesh size along the heating zone, more accurate is the result. For Plasma-jet forming, temperature gradient along thickness can be accurately measured when greater number of elements are available along the thickness of the metal plate where heat is being induced. Adopting a finer mesh for large deformations in ANSYS is of greater significance as better aspect ratios will also reduce any distortion errors and further deviance of the result from the exact solution. Hence a mapped mesh has been used with proper element size specifications along the heating zone such that the aspect ratio of each element is within an acceptable range (1-5). The rest of the metal plate has been graded with a free mesh.

Use of adaptive remeshing and rezoning will further increase the accuracy of the solution as dynamic mesh modification along the deformed or distorted elements is possible. In the current version of ANSYS, adaptive remeshing and rezoning are not available for 3-D transient analysis. A sequentially coupled thermo-mechanical simulation is a complex procedure that needs to be controlled by a structured algorithm. Convergence of solution for these nonlinear problems is generally possible by the use of a Newton-Raphson method. While many numerical integration schemes are available, Newton-Raphson method is a widely used numerical approximation methods along with implicit numerical integration methods for nonlinear structural problems.

For large deflection analysis, the resultant stiffness matrix should be a function of deflection [40] [41]. Nonlinear analysis requires large computation times and hence it is important to utilize all possible simplification in order to improve convergence of the solution. Also the path dependency of the solution during nonlinear material behavior may also affect the final result attained. Geometrical nonlinearities arise generally in a nonlinear structural analysis when large strains are produced especially in metal forming. A moving heat source will require the heat flux to be applied as a surface load on each element and be moved along the scanning path from one element to another depending on the time and velocity of the plasma torch. The heat flux induced will be used to determine the temperature field distribution along the metal plate. These temperatures will then be applied as body loads in a transient structural analysis to measure the deformation obtained. Given the complexity of the problem, execution of an algorithm in ANSYS has been performed using ANSYS Parametric Design Language (APDL) [42]. APDL provides a user controlled step by step instructions that interact with ANSYS to provide a flexible and efficient simulation procedure [43]. In a transient analysis setting up the number of load steps, substeps and equilibrium iterations is necessary. This will enable a proper response of the structure at specific points in time as desired. The programming methodology using APDL is available in ANSYS Documentation [42]. Thermo-mechanical analysis of plasma-jet forming is a two step process. Transient thermal analysis is first performed and is followed by nonlinear transient structural analysis. The figure in the next page illustrates the algorithm used for finite element simulation.

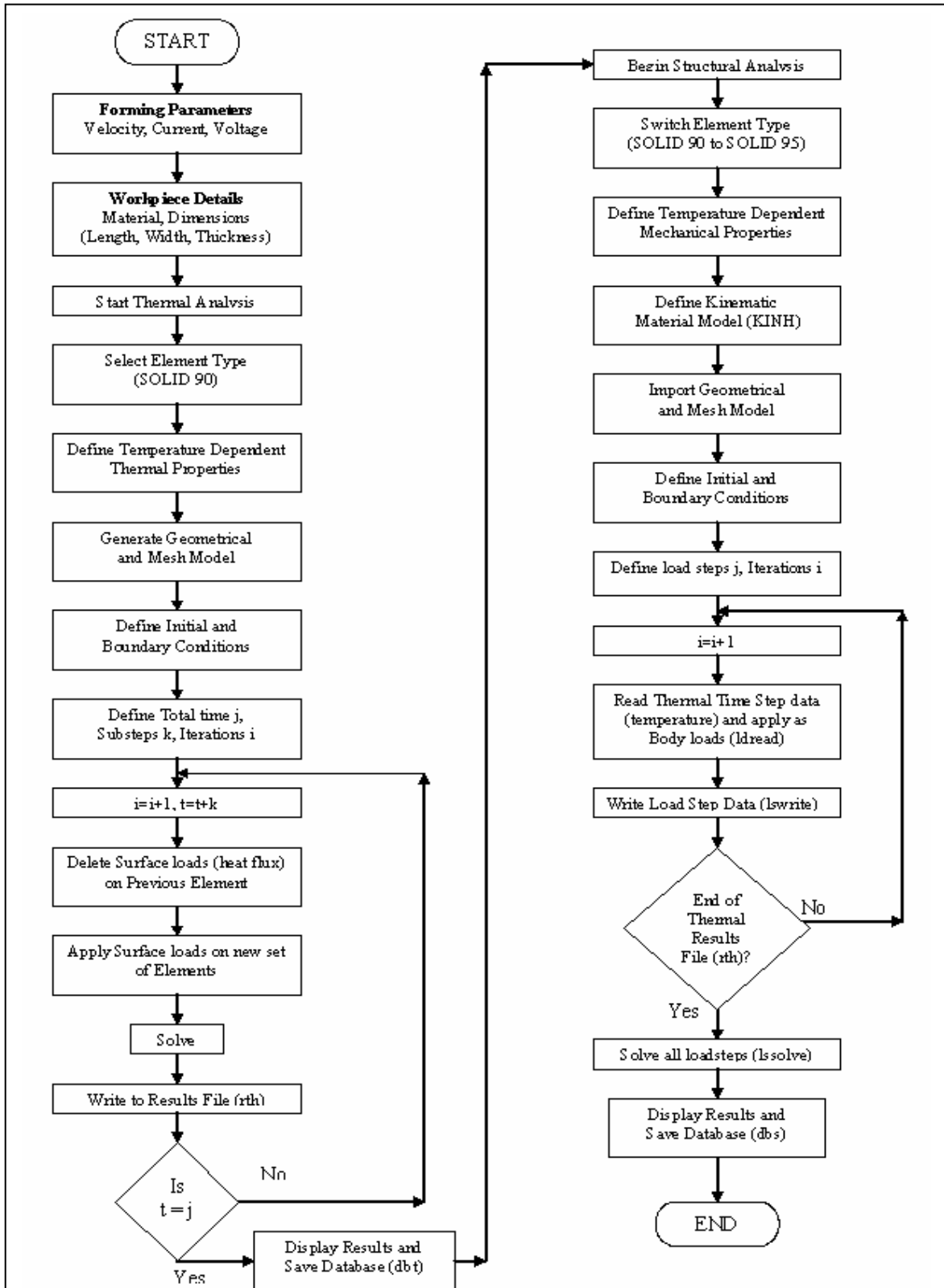
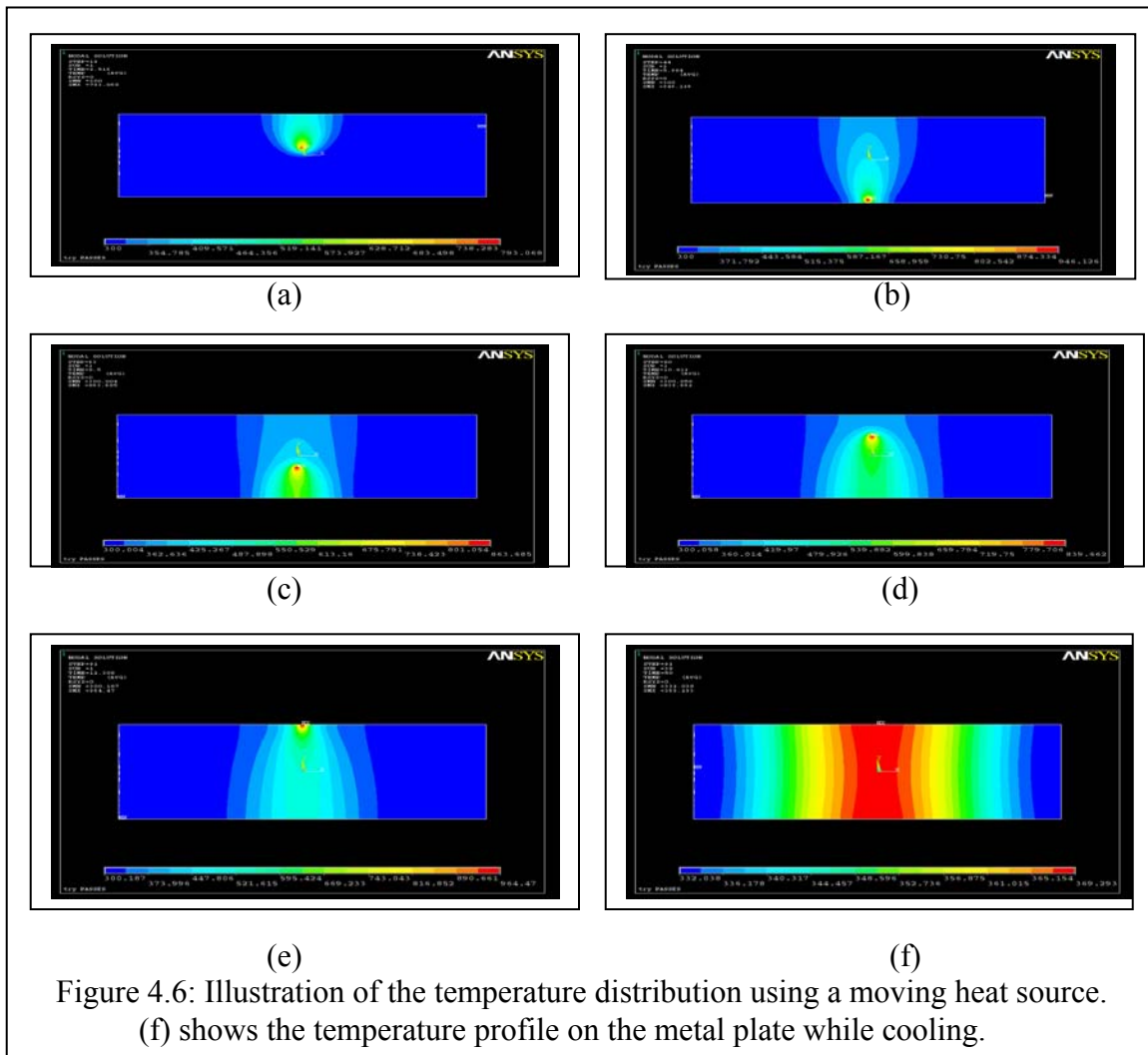
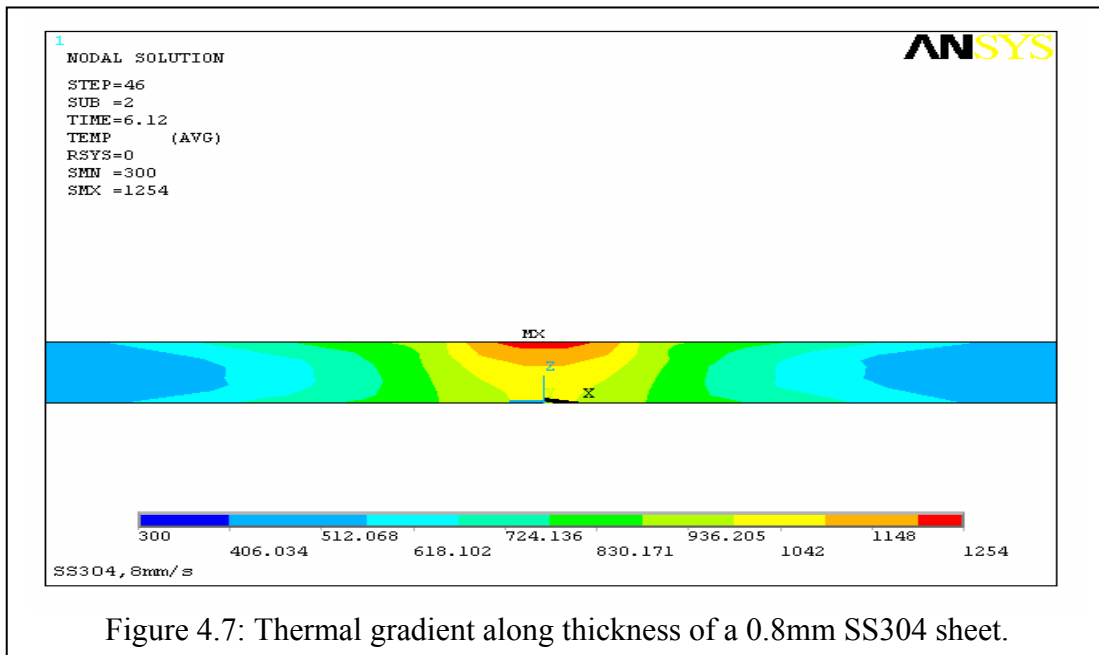


Figure 4.5: Flow diagram of sequentially coupled thermal-structural analysis of plasma-jet forming.

The heat flux induced on the top surface of the sheet metal is dependent on the current, voltage, velocity of the torch and the orifice diameter of the width of the heating zone as explained in equation 5. The heat transfer coefficient f for a plasma heat source lies between 0.8 and 0.9. f is taken as 0.85 in this simulation. The coolant at the bottom surface is maintained at a constant temperature of 298 K. The moving heat source is simulated by passing the heat flux to be induced on the top surface from one element to another. The surface load applied in the previous element is deleted and then applied on the next set of elements on the predetermined line of heating. The coolant is applied on the bottom surface of the sheet metal and moves along with the plasma torch along the heating zone.



As shown in the figure 4.6, major changes in the temperatures on the surface of the sheet metal occur mainly on the set of elements along the heating line. The temperature on the top surface increases as the number of plasma-jet scans increase, but the coolant maintains the bottom surface at relatively low temperatures creating a gradient along the thickness. When the sheet metal is cooled down during the cooling phase, the temperature spreads through the metal until the whole plate achieves uniform temperature. The transient thermal analysis of plasma-jet forming follows the thermal gradient mechanism (section 2.2) to induce stresses required for bending. The temperature gradient along the thickness of the metal plate determines the amount of plastic deformation possible.



The surface temperatures increase as the number of plasma scans increase but remain below the melting point of the material. Also as the heat source moves away from an element gradual decrease in temperature takes place. Any residual temperature present in the metal should help in increasing the bending as a hotter metal is easier to form than a colder metal.

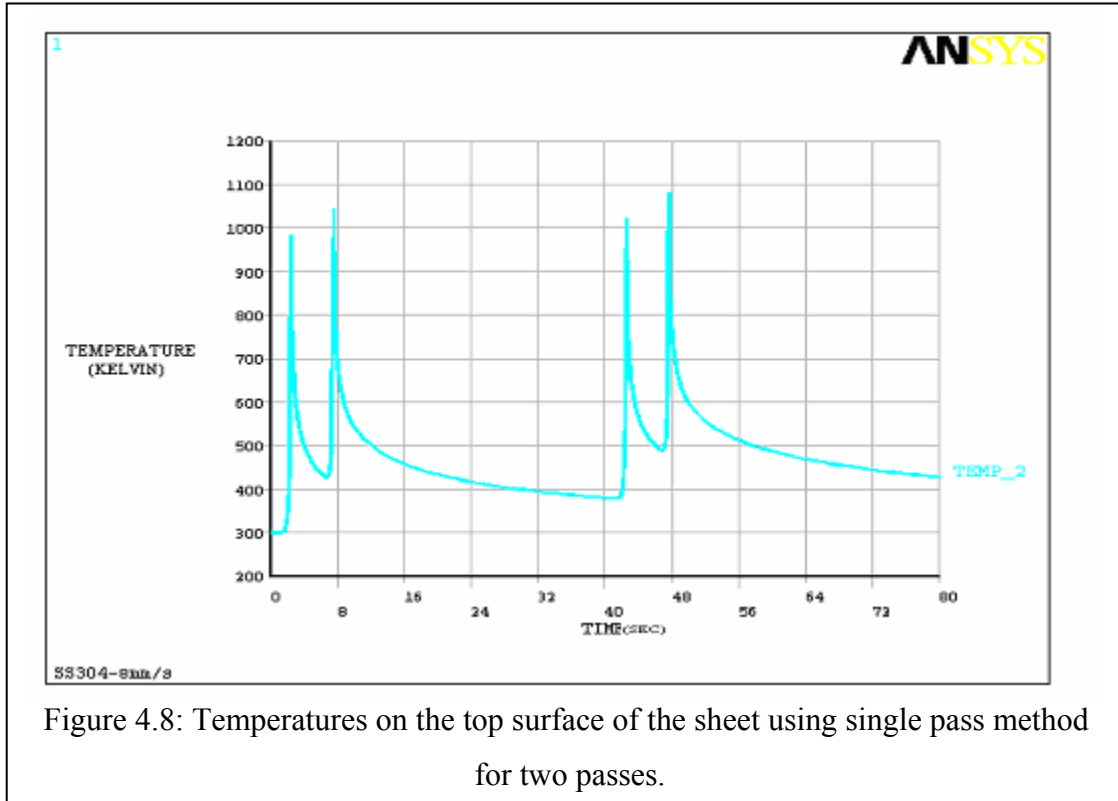
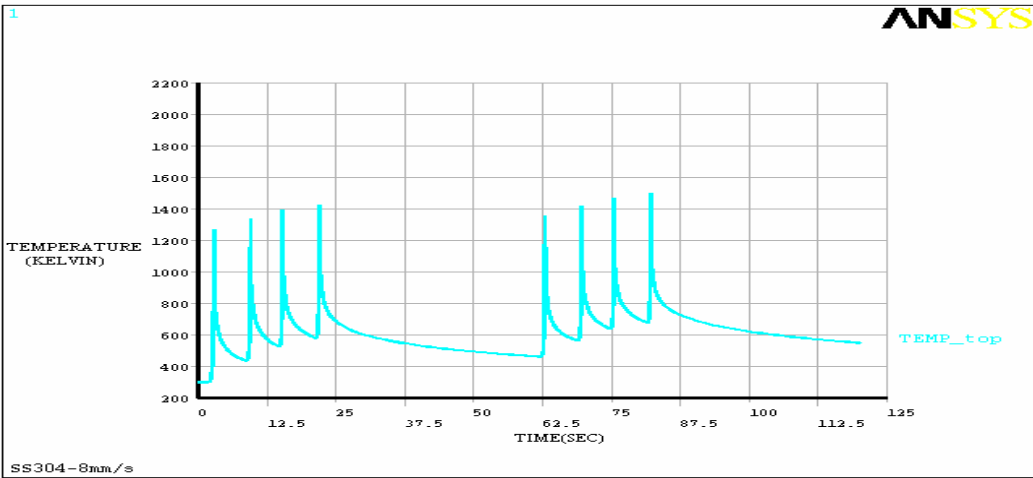
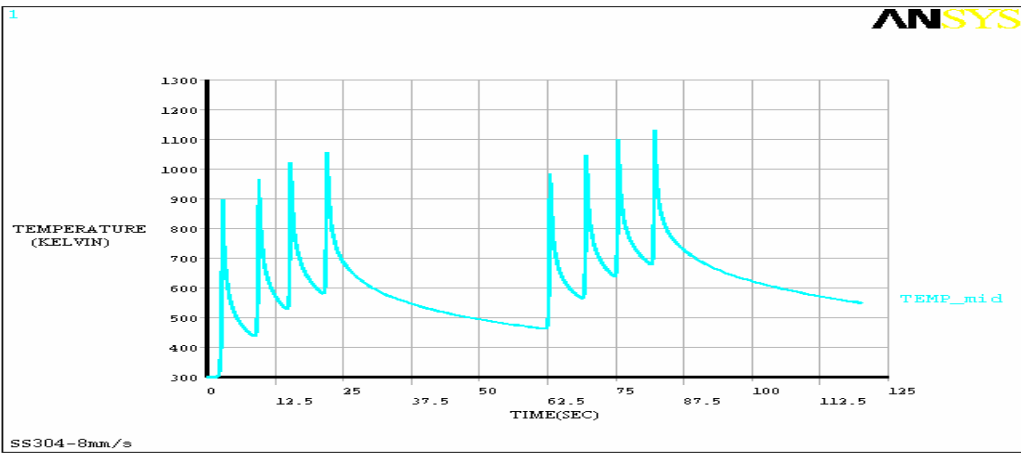


Figure 4.8: Temperatures on the top surface of the sheet using single pass method for two passes.

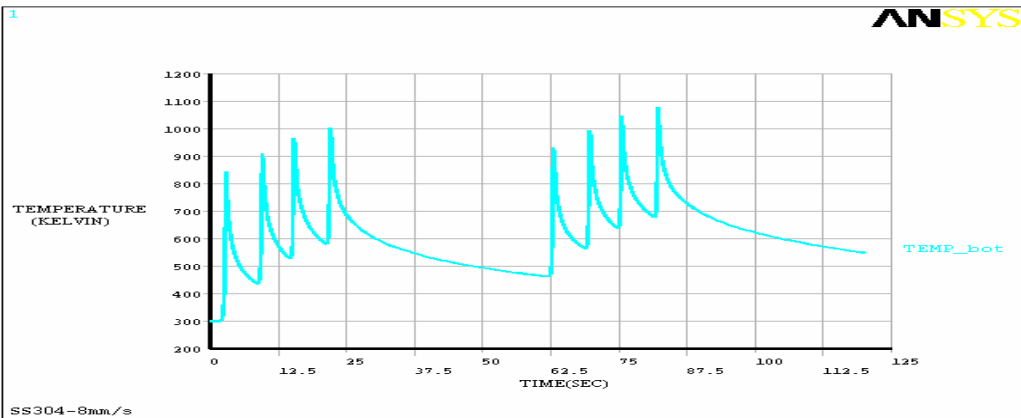
Figure above describes the temperature profile on the top surface of a sheet metal during plasma-jet forming. Sudden rise in temperature at a node is due to the heat flux induced by the moving heat source. As the heat source moves away from the node, temperatures decrease because of the existence of a coolant on the bottom surface and ambient conditions around the sheet. The temperatures continue to rise as the plasma torch scans through the top surface and decrease along the thickness. The slower the torch speed greater is the surface temperature on the surface of the sheet metal. Slower torch speeds allow the heat flux to be applied for more time than that at higher torch speeds and this allows a greater thermal gradient to be created at relatively faster rate thereby ensuring high bending angles.



4.9a: Temperature behavior on the top surface ($h=0.8\text{mm}$).



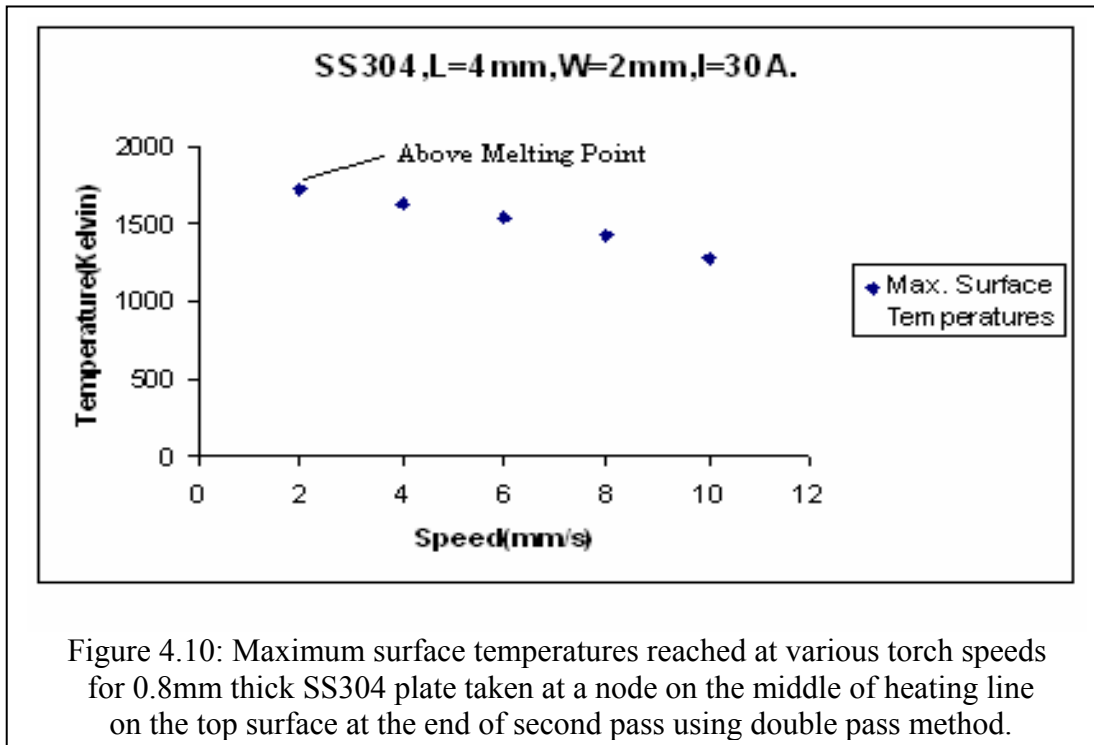
4.9b: Surface temperature at a node in the mid-thickness ($h=0.4\text{mm}$).



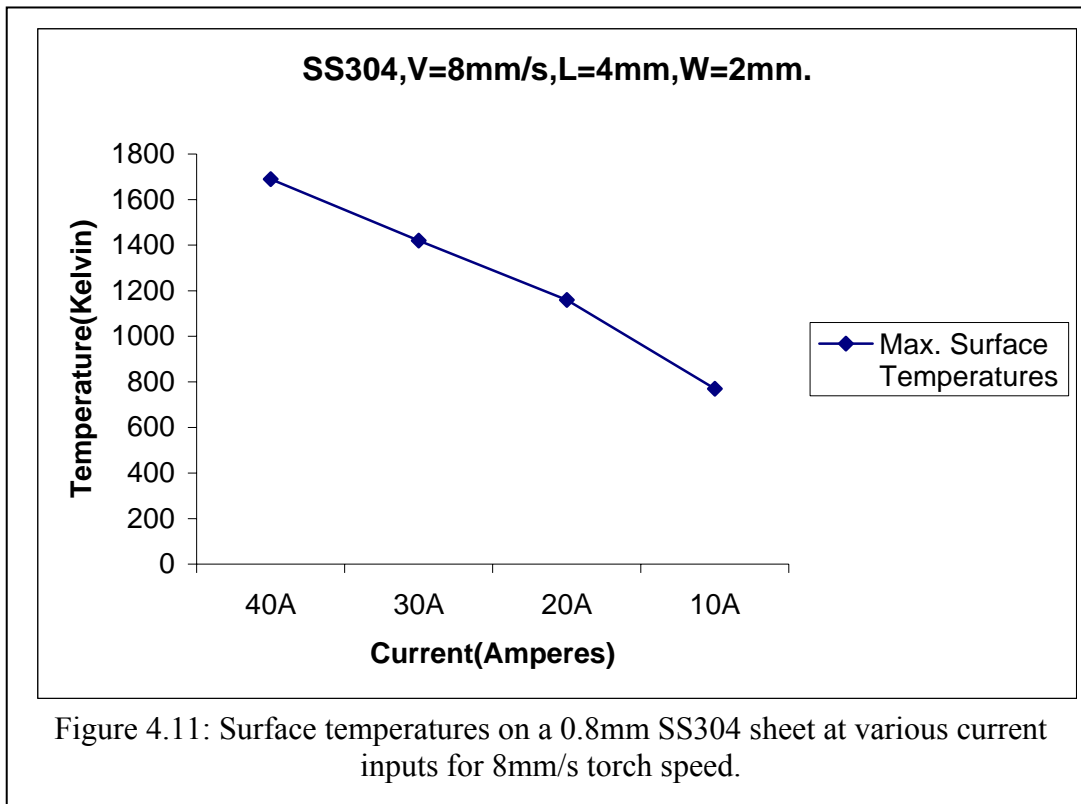
4.9c: Temperatures at the bottom surface ($h=0\text{mm}$).

Figure 4.9: Surface temperatures with time using double pass method for SS304, 0.8mm thick plate at 8mm/s torch speed and 30A current.

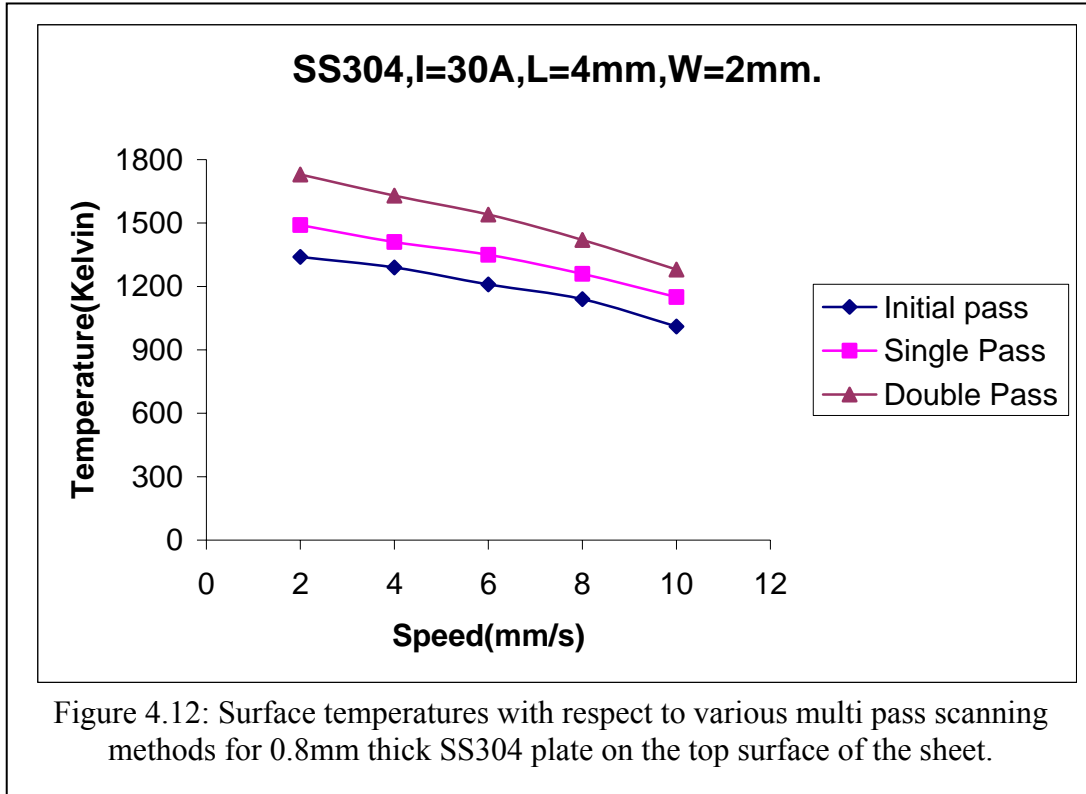
Surface temperatures prove to be vital for thermal gradient mechanism to provide large bending angles. While torch speed was observed to be a major parameter to increase the surface temperatures, increase in the overall power input from the plasma torch will also increase the surface temperatures. Also uses of alternate heating and cooling methods have helped in maintaining larger temperature gradient during multipass forming. Various scanning methods used in plasma-jet forming have been explained earlier in section 3.6.



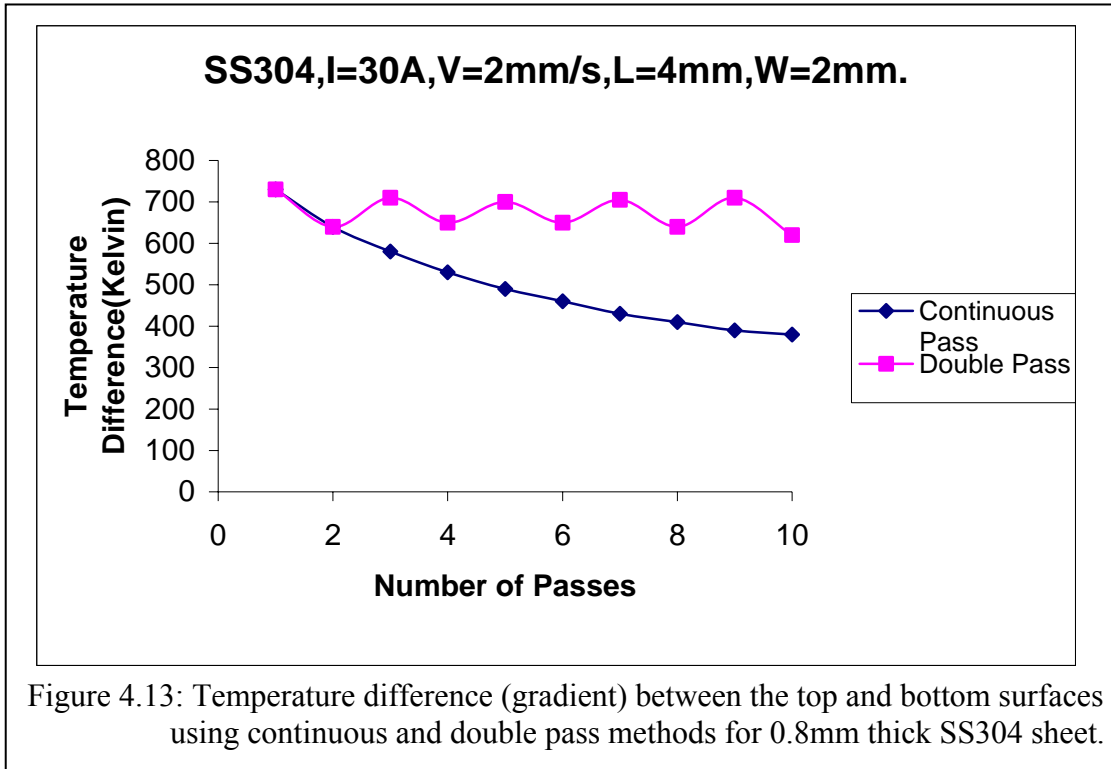
It has been observed that at a torch speed of 2mm/s, the surface temperature of the 0.8mm SS304 plate is 1780 K, exceeding the melting point of the material (1690 K). Similar observation has been made during experiments where specimens have melted at low torch speed of 2mm/s.



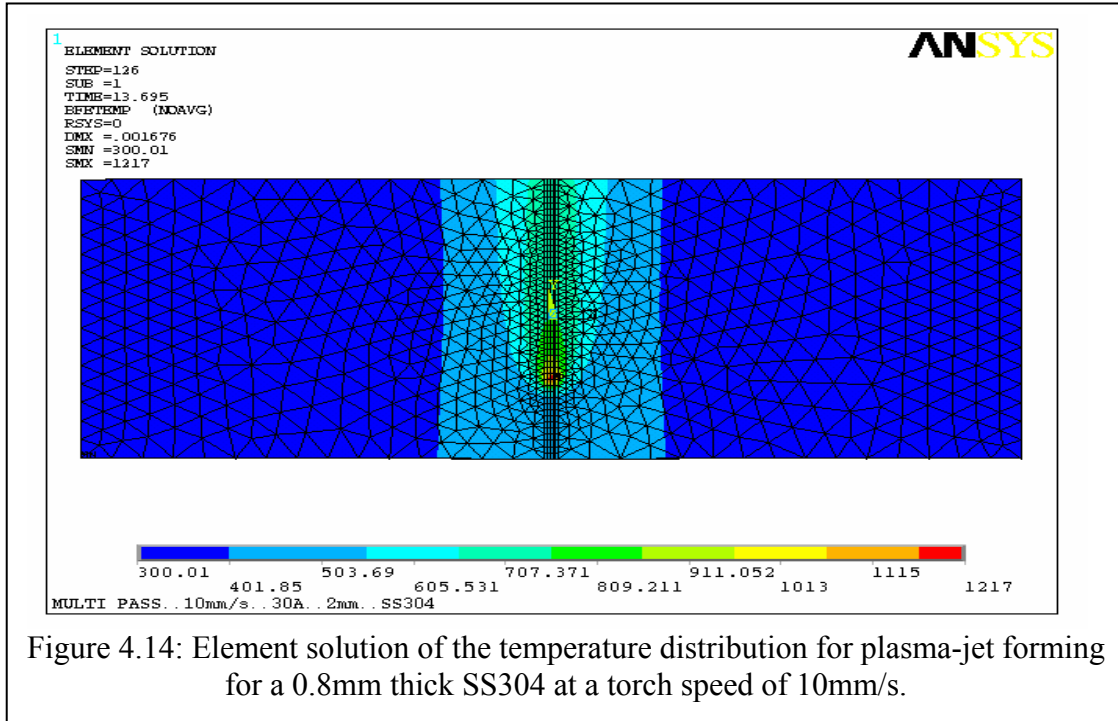
The surface temperatures on the metal surface increase with decrease in torch speeds and also with increase in the current input. While a slower velocity of the plasma torch allows heat flux to be induced for a greater time, increase in current input will increase the amount of heat flux to be induced on the surface of the sheet metal. For materials of low thermal conductivity and less thickness, use of higher power (current) inputs will result in melting of the material. Proper coupling of the power and torch speeds will hence provide an optimum bending value. Also higher surface temperatures during heating will result in larger thermal gradient as coolant manages to keep the temperature at the bottom surface consistently at low temperatures. Large thermal stresses are created and lead to permanent deformation in the sheet along the heat affected zone. Different scanning methods (section 3.3) analyzed during experiments have shown significant increase in the bending value. This can be validated with an observation of the surface temperatures and temperature gradients being created when these methods are used.



Surface temperatures are maximum during double pass method and this can be attributed to greater number of scans being performed when compared with any other scanning method used. While continuous number of scans increases the surface temperature, thermal gradient reduces gradually as temperatures penetrate through the internal layers of the metal. Use of alternate heating and cooling will help in maintaining a constant thermal gradient as heating after subsequent cooling will generate the same amount of temperature as in previous passes. The surface temperatures although high enough, do not exceed the melting point of the material. For materials of lower thermal conductivity, less number of passes are required to produce high temperatures that create a large thermal gradient to enunciate plastic deformation, where as for materials of high conductivity sustaining a large value of thermal gradient becomes difficult and the temperature difference reduced gradually.



As shown in the figure above, thermal gradient decreased rapidly with increase in number of passes for a continuous scanning method while a consistent thermal gradient was maintained in a double pass method. In a double pass method, reheating allows the material to reach a peak temperature thereby allowing it to maintain a thermal gradient equivalent to those in previous passes. Use of double pass method hence has been advantageous as a constant large thermal gradient led to increased amount of bending (fig 3.5-3.8).



The width of the heating zone is the sum of the orifice diameter of the plasma torch and the width covered by the torch due to raster. A constant orifice diameter of 2mm was used and the raster for the torch was set to 1mm. Hence a total width of 3mm was heated by the moving heat source. Simulations have been performed as in experiments with the heating width along the central axis. As observed in Figure 4.1.4, the moving heat source applies the localized heat flux only on the set of elements associated in the heating width. As the heat source traverses forward and backward along the line of heating, the temperatures dissipate through the thickness and along the surface. The temperature distribution above illustrates similar behavior with an overview of the elements affected by the induced heat flux and the total heat affected zone.

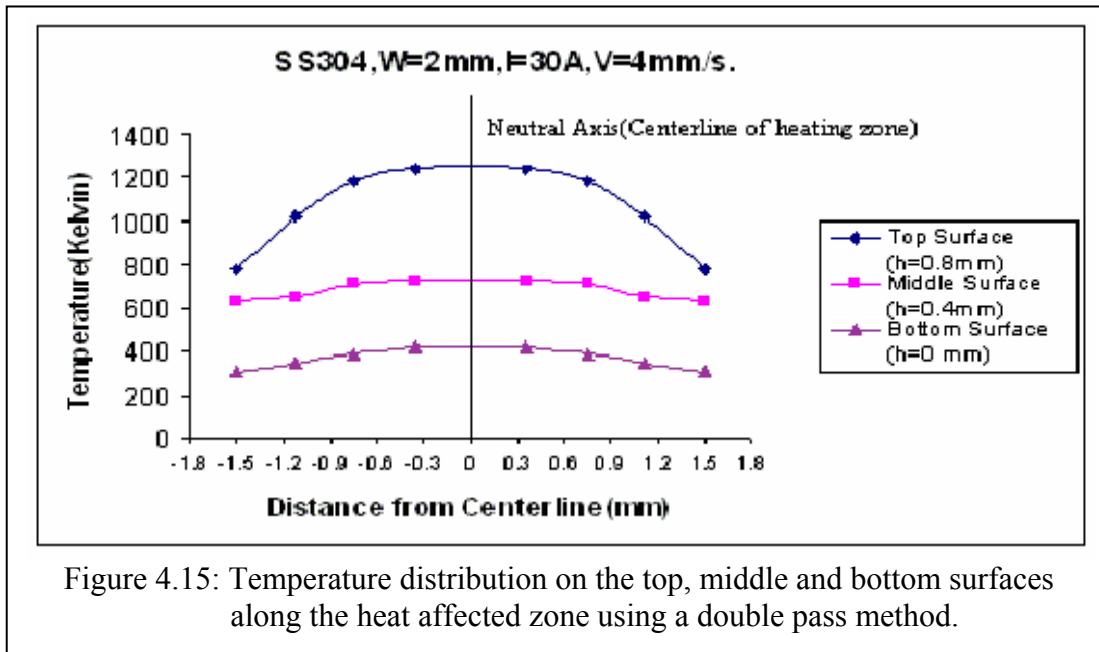


Figure 4.15: Temperature distribution on the top, middle and bottom surfaces along the heat affected zone using a double pass method.

It has been observed that the temperature distribution was symmetrical along the line of heating and the surface temperature decreased as the distance from the neutral axis increased.

All the temperatures obtained at various time steps by the application of surface loads from transient thermal analysis are transferred to structural analysis as body loads to study the stress distribution and measure the deformation in the sheet. The material model shown in Figure 4.3 has been used for the simulation. The geometrical shape and mesh distribution are perfectly imported from the thermal analysis to perform the structural analysis. The temperatures obtained from the thermal analysis are imported at every load step and applied on the physical model based on the time step, velocity and position of the heat source.

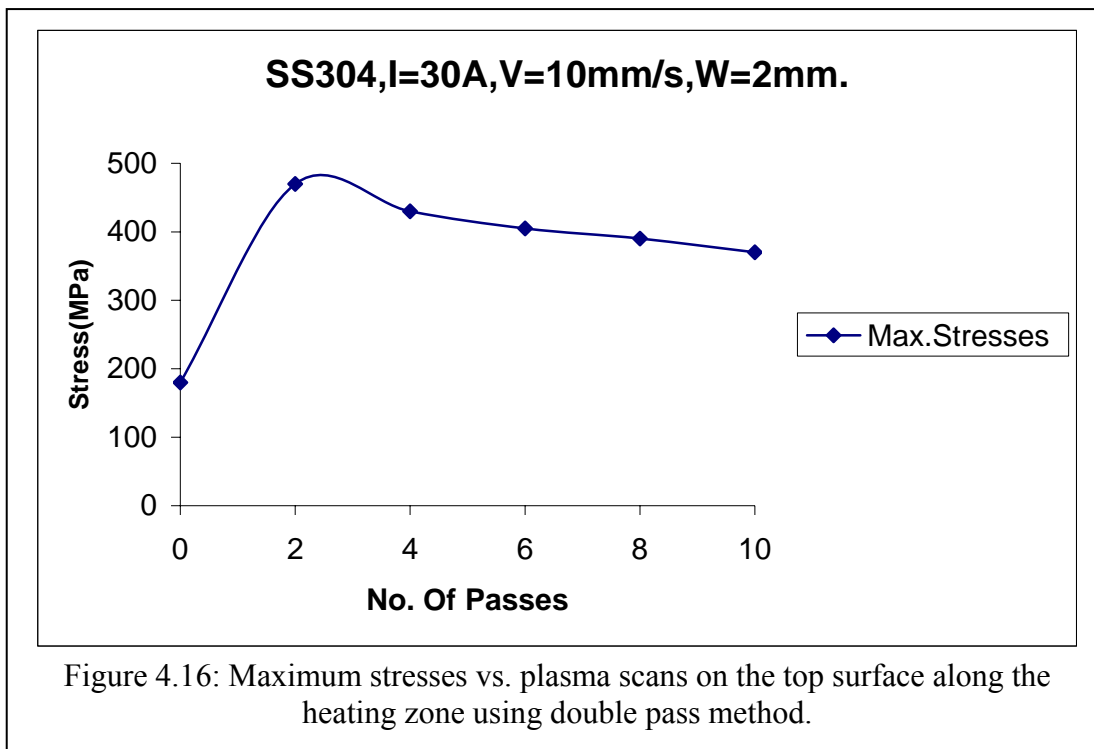
The deformation in the structure is based on the material model and depends on the value of the stresses and corresponding strains developed. The multilinear kinematic hardening model uses the Besseling model (overlay model). Bauschinger effect is included in this model [42]. The assumption is that the corresponding points on the different stress-strain curves represent the temperature dependent yield behavior of a particular sublayer.

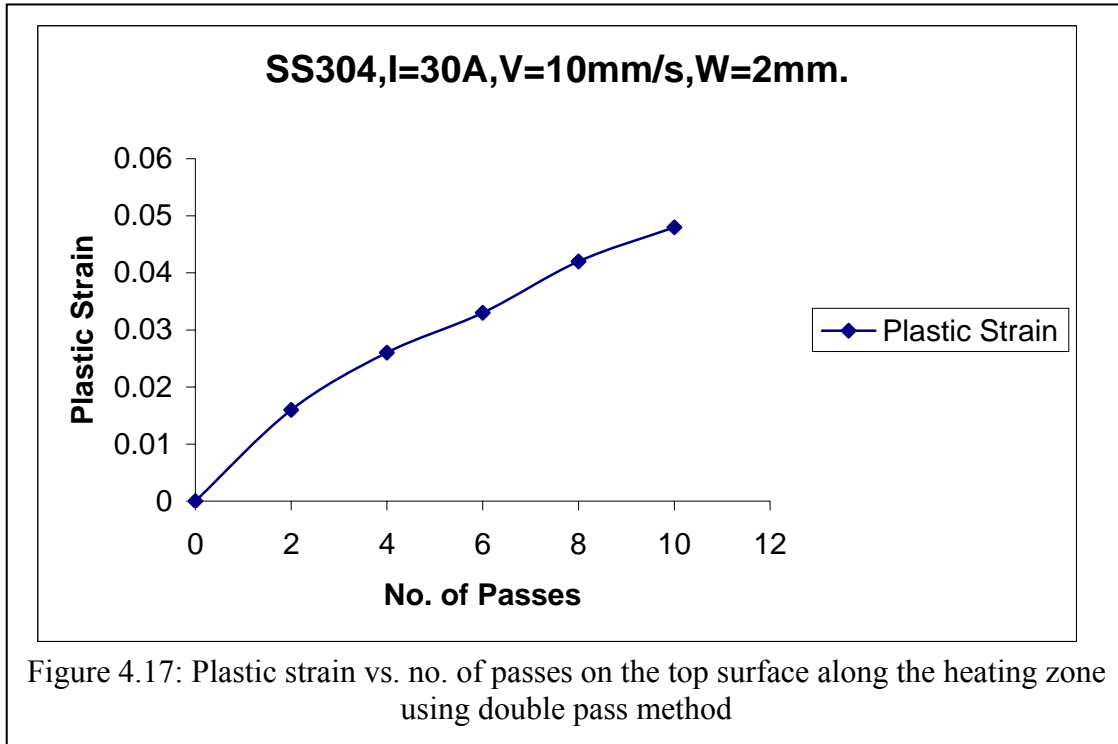
The plastic strains in ANSYS are calculated based on the formula:

$$\text{Effective Plastic strain} = \text{Total True Strain} - \text{True Stress}/Y. \quad (6)$$

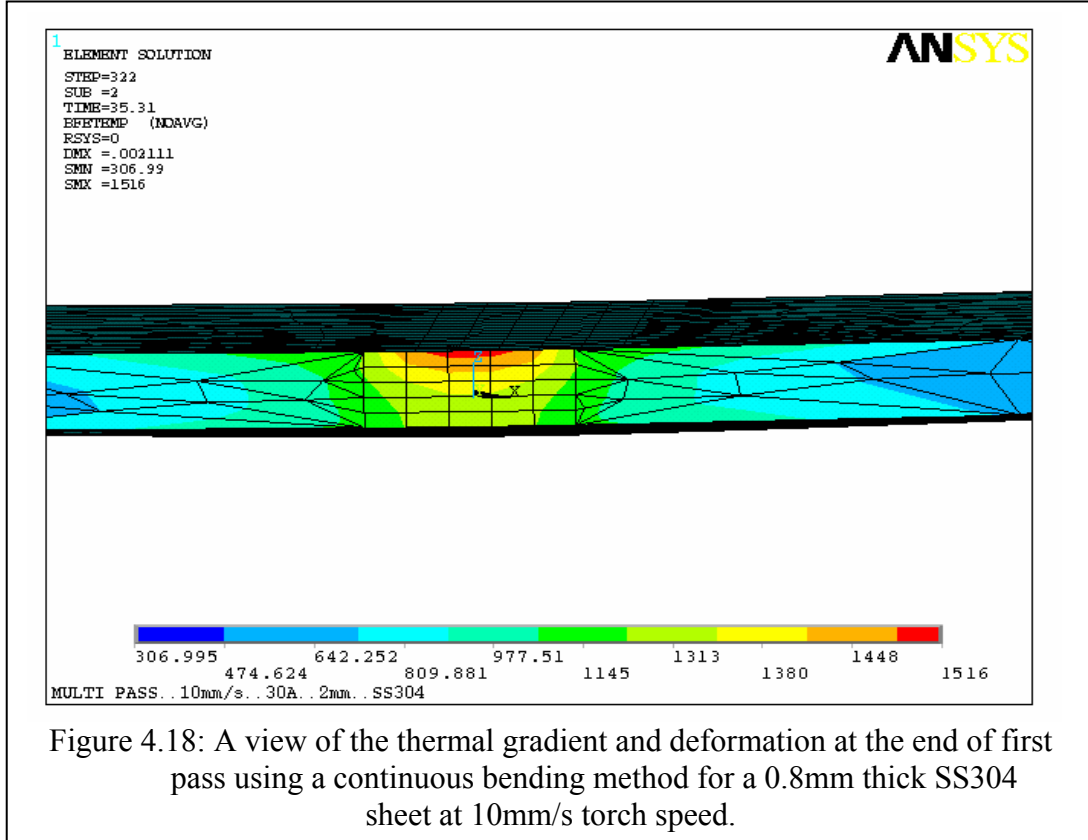
As the stress value increases, recoverable strain (true stress/Y) value also increases. The material model (σ - ϵ curve) used for input needs to be accurate enough in a nonlinear analysis to obtain necessary measurements.

Also when the corresponding stresses generated are high enough that they exceed the yield strength of the material, inelastic (permanent) deformation occurs. Yield strength is a major parameter on which deformation is dependent in plasma-jet forming. Higher the yield strength of the material less is the deformation as more plasma-jet scans are required to generate high stress-strain values. Generation of these stresses is also dependent on the thermal gradient. The increase in temperature of the body and the temperature difference along the thickness help in enhancing the stresses induced in the structure. Presence of any residual temperatures before reheating using a single pass method and double pass method helps in increasing bending by reducing the flow stress [25].

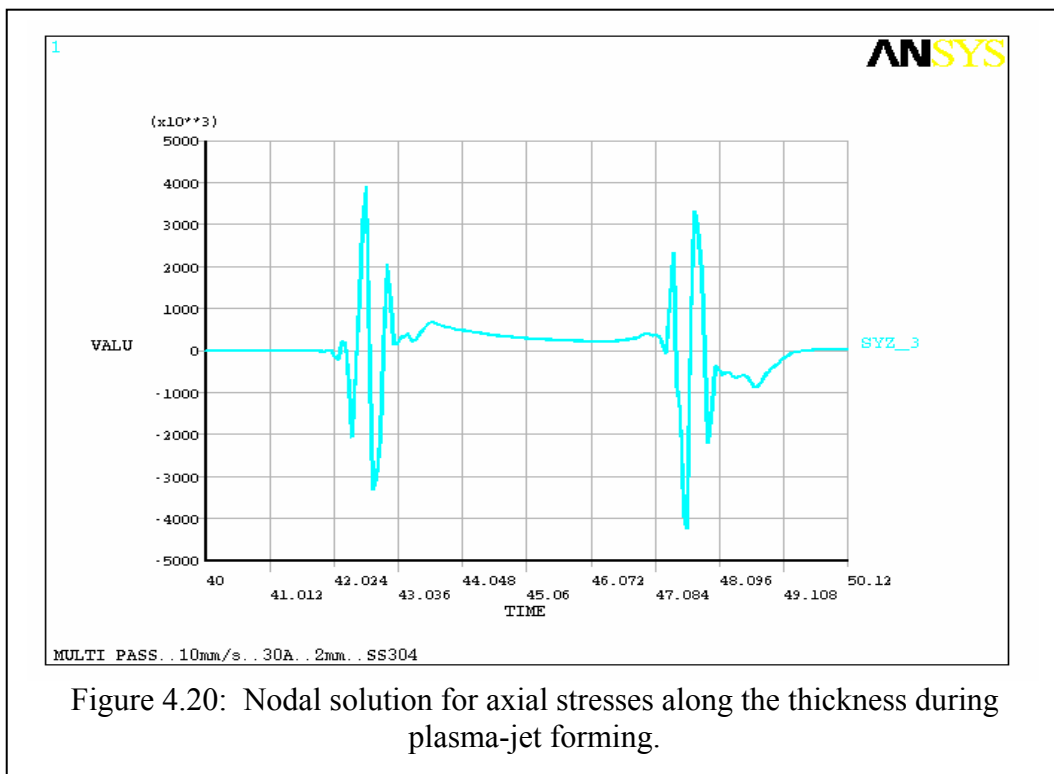
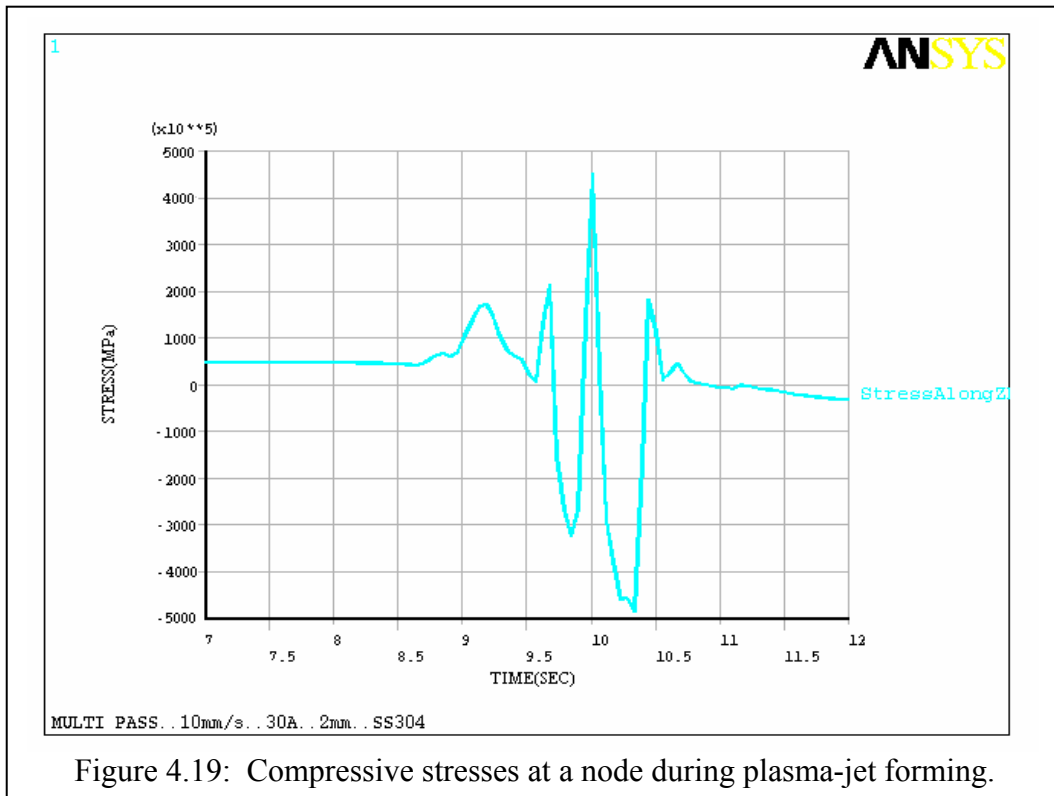


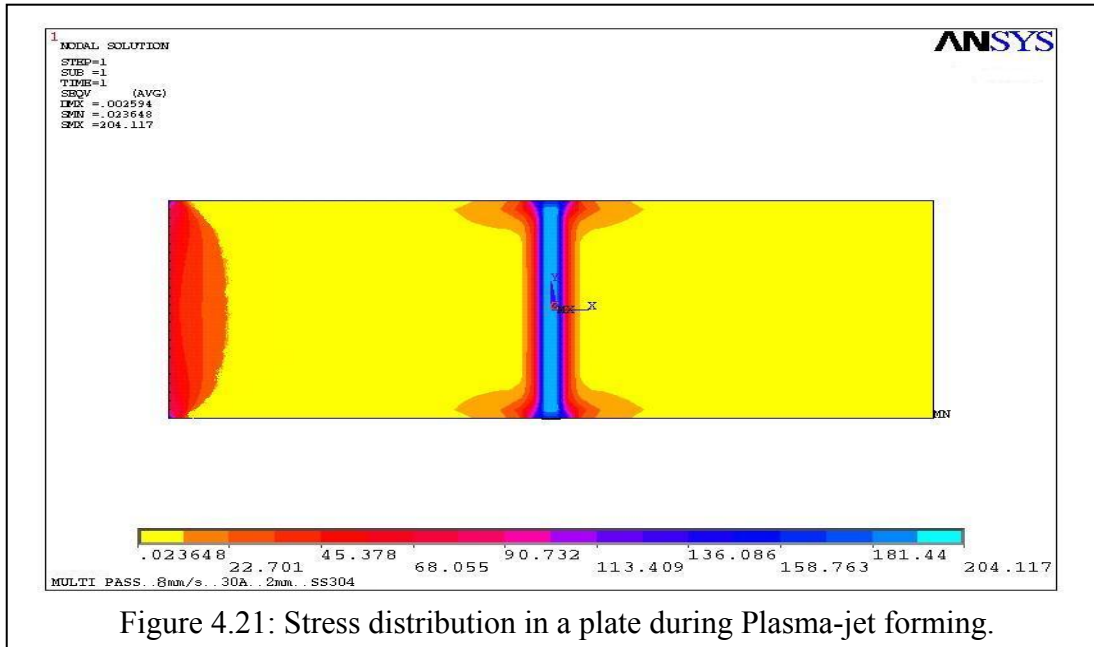


The stresses in the structure increase initially and gradually decrease but still remain in the plastic state. The yield strength of SS304 is approximately 197 Mpa and decreases with increase of temperature. Bending using Plasma-jet forming is hence a combination of the thermal gradient and the stresses generated that lead to a plastic deformation. A constant peak thermal gradient and high surface temperatures help in inducing necessary thermal stresses. Also, temperatures on the surface are determined by the combination of current input (power) and torch speed used.

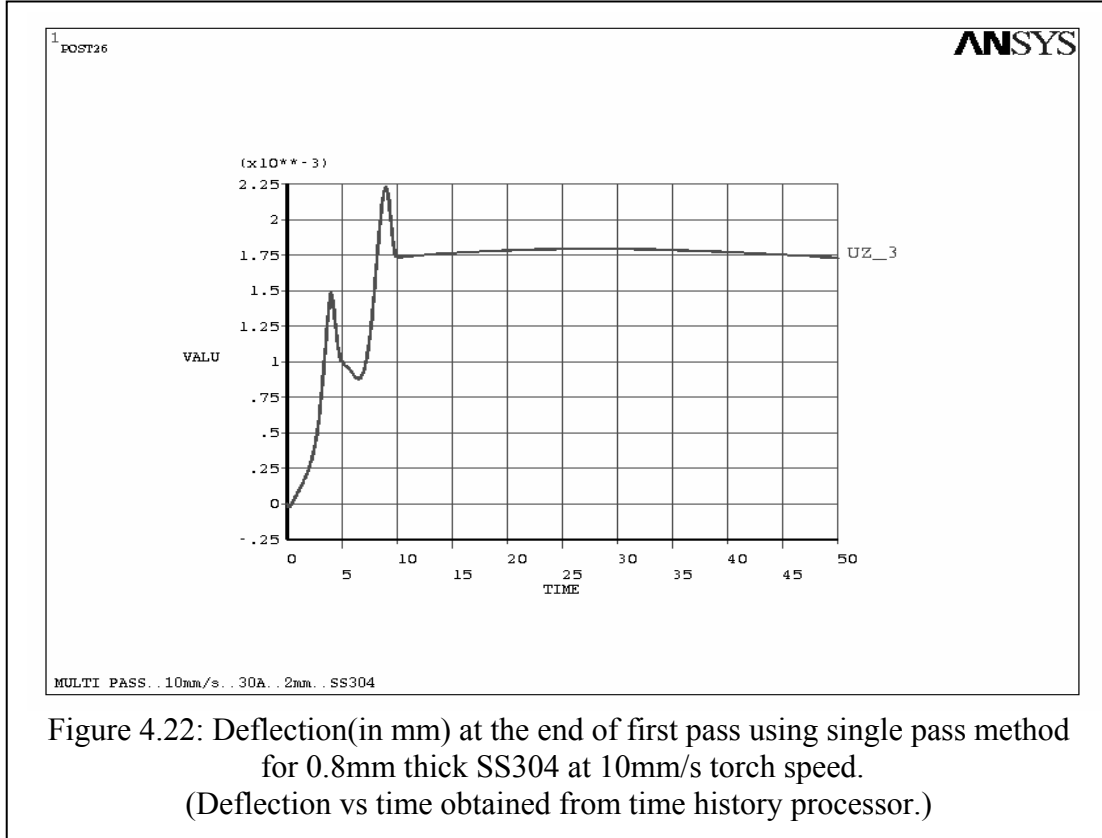


The residual stresses at the end of cooling during plasma-jet forming are found to be minimal and the effect of these residual stresses on the bending rate in further passes is negligible. The stresses on an element during heating are compressive and tensile stresses generate as the material cools down. Figure 4.19 and 4.20 show the stress distribution during plasma-jet forming. The stresses leftover (residual) at the end of cooling are observed to be close to be very low (0-110 Mpa). Also the residual stress values (Figure 4.20) after cooling do not exceed the yield strength value and hence the net effect of these stresses on the deformation is minimum.





The stresses induced in the structure are found to be symmetrical along the line of heating(Y axis). The maximum stress region lies along the heating width of 3mm. Stresses are maximum at the center of the neutral axis along line of heating and gradually reduce away from the center. These high stresses along the plasma scanned region lead to a permanent deformation along its axis. The line of heating hence forms the bending line and actuates incremental bending as the number of irradiations increase. Residual temperatures have a direct effect on bending. While presence of high temperatures reduce the flow stress to aid bending further, but there are equal chances for reduction of thermal gradient. The stresses induced in the structure lead to the permanent deformation, bending angle is measured based on the deflection obtained along the z-axis. The net deflection obtained in plasma-jet forming is positive and hence an upward bending is observed.



The deflection in the structure is measured from the deflection vs time measurements in the time history post processor of ANSYS. These time-based measurements help us in measuring the deflection after each pass at a specific time on specific node based on the iterations performed. Deflection obtained above in Figure 4.22 was measured to be equivalent to a bending angle of 1.98° . Hence for a 10mm/s torch speed, at a 30A current input a positive bending angle of 2° was obtained on 0.8mm thick SS304 sheet metal. While all major input parameters that determine the bending have been examined, effect of offset distance on bending has not been considered in the present analysis.

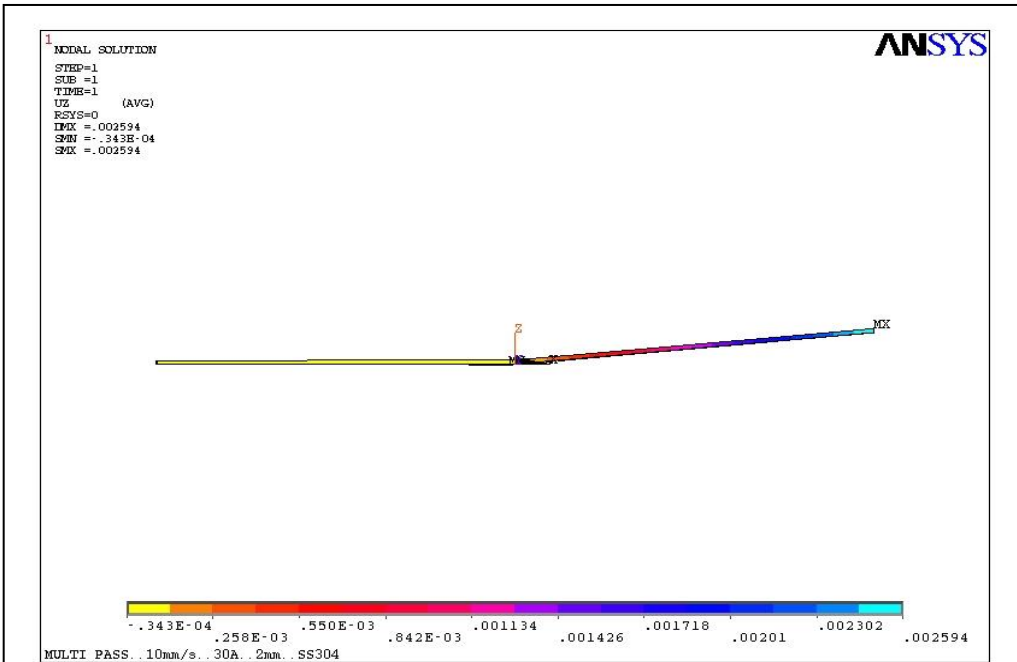


Figure 4.23a: Deflection along the deformed edge obtained at 10mm/s torch speed on 0.8mm thick SS304 sheet.

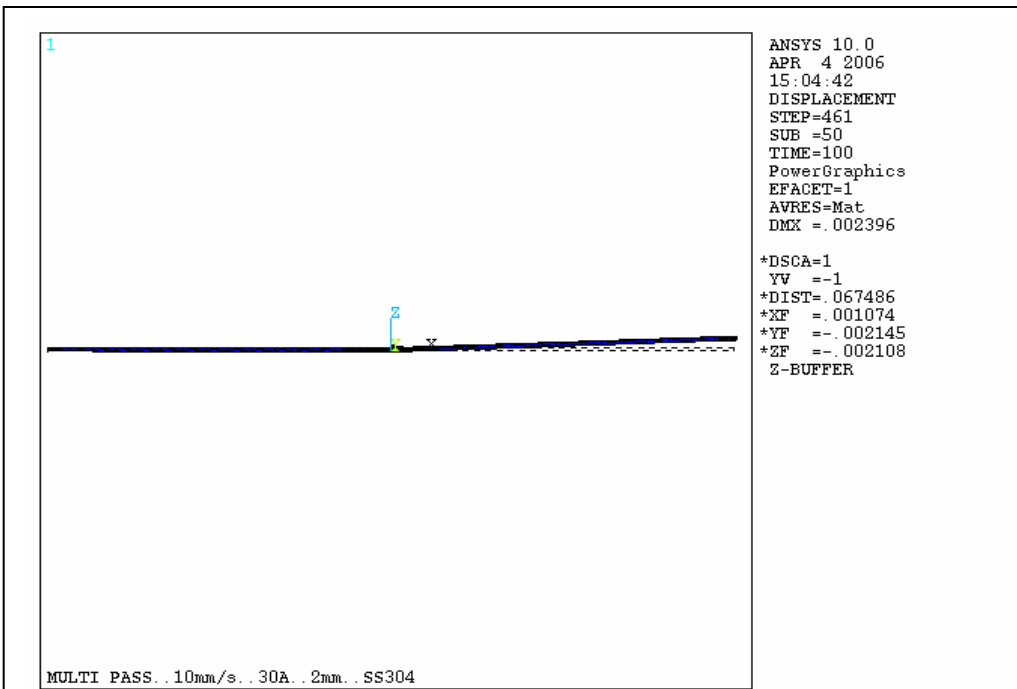
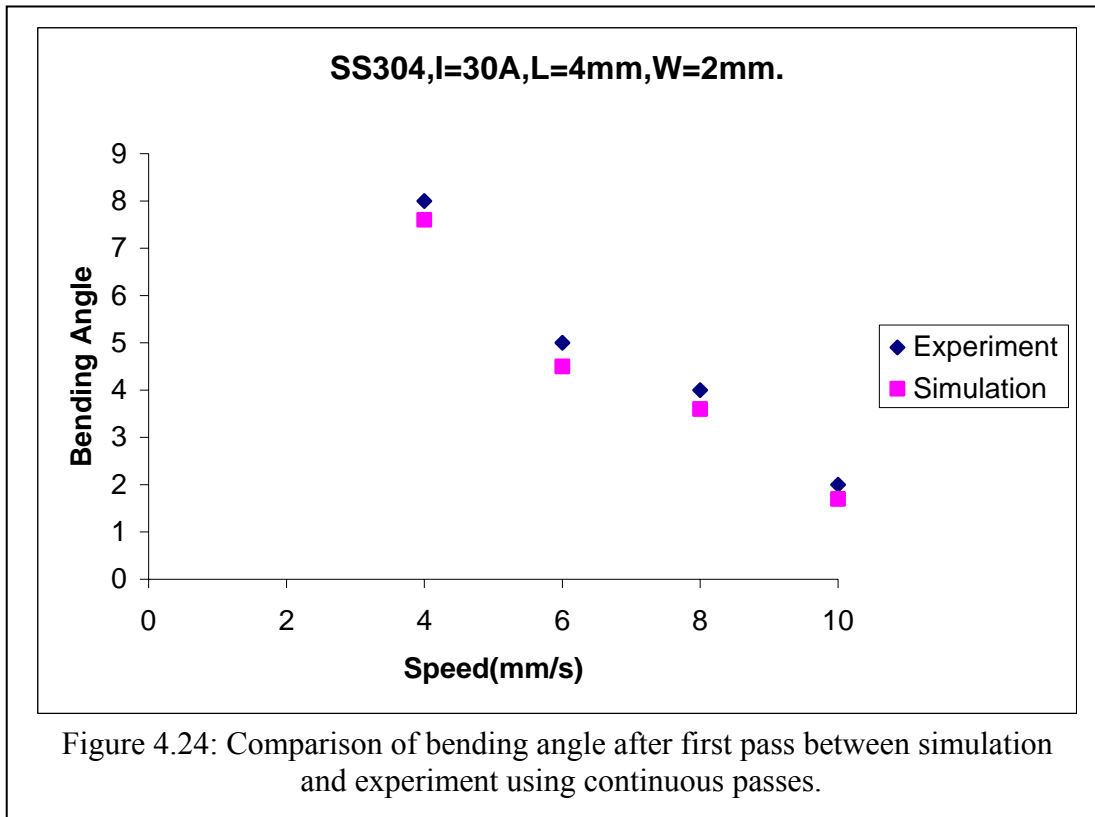


Figure 4.23b: Comparison of bending with deformed and undeformed edge (initial state) at 10mm/s torch speed on 0.8mm thick SS304 sheet.

Figure 4.23: A view of deflection obtained after a single pass using plasma-jet forming.

The bending angle obtained after each pass can thus be predicted for any change in velocity, power and orifice diameter. This dissertation mainly focuses on analysis of plasma-jet forming with SS304 of thickness 0.8mm, orifice diameter 2mm and current input of 30A, while the velocity of the plasma torch was varied from 2mm/s to 10mm/s.

The bending angle after the first pass has been validated with those observed during experiments (Figure 4.24).



The bending angle obtained using thermo-mechanical analysis for plasma-jet forming has a near accuracy between 90% and 95%. The validation of the bending angle has been done for torch speeds from 4mm/s to 10mm/s. While melting was observed during experiments for a speed of 2mm/s, the peak temperatures observed during simulation exceeded the melting point of the material (Figure 4.10). The bending angle using simulation has been found to be accurate only for a single pass. The thermal analysis can predict the temperatures during multiple plasma scans but the structural analysis has provided accurate results only till the end of first pass.

The bending angle decreased significantly with increase in number of passes for multi-pass analysis when reheating was initiated the next pass after subsequent cooling (Figure 4.25). A Multi pass plasma-jet forming simulation requires accurate material model that can predict the nonlinear material behavior after each pass. The material model used in this simulation fits only for the initial heating and cooling process. When the metal plate is reheated, a new material model input is required with true values of yield stress and flow stress along the line of heating. These values can be obtained from experiments and tensile tests on sectioned materials along the line of heating after each pass. Predicting a generalized material model for the value of yield stress and flow stress after each pass is a herculean task, as it depends on the velocity of the plasma torch and the power input. Any variation of these input values will change the surface temperature and hence the values of flow stress and corresponding yield stress.

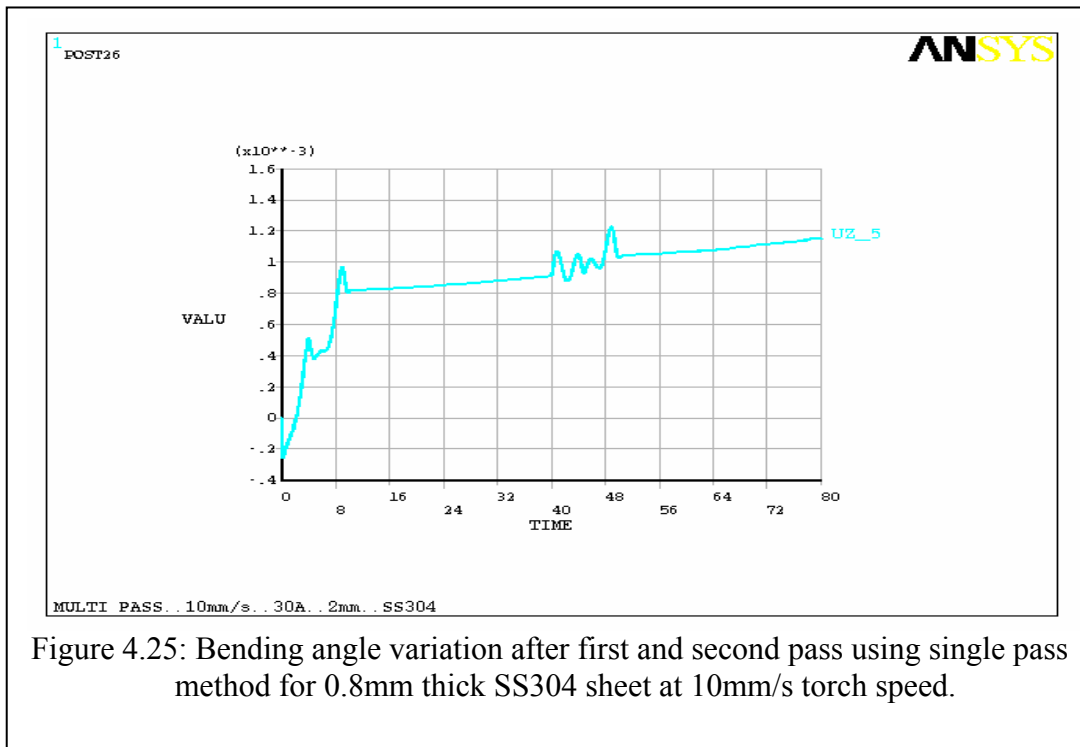


Figure 4.25: Bending angle variation after first and second pass using single pass method for 0.8mm thick SS304 sheet at 10mm/s torch speed.

The table below summarizes the observations from both experimental and numerical investigation.

Table 4.4: Bending angle at various speeds for 0.8mm thick SS304.

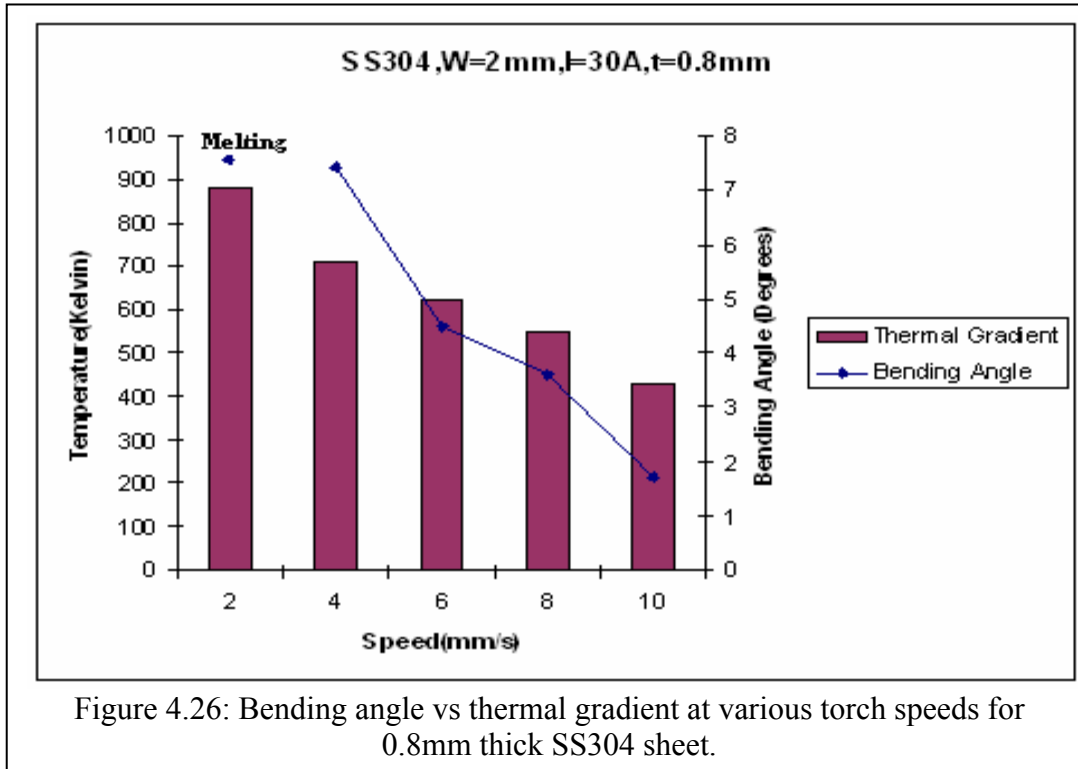
S.No	Current	Velocity	Thermal Gradient	Bending Angle		Error
				Experiment	Simulation	
1	30A	2mm/s	880K	---	---	---
2	30A	4mm/s	710K	7.9	7.6	3.94%
3	30A	6mm/s	620K	4.8	4.6	4.34%
4	30A	8mm/s	550K	3.9	3.7	5.40%
5	30A	10mm/s	430K	1.9	1.8	5.55%

4.4 Discussion

Thermo-mechanical simulation using ANSYS has been mainly performed to study the stress distribution and determine the peak surface temperatures on the sheet so as to determine optimum parameters that effect plasma-jet forming. While velocity, current, offset distance and orifice diameter are the main input parameters on which bending angle is dependent, it has been observed during simulation that variation of current input and torch speed have a greater effect on bending. Coupling of current input and velocity of the plasma torch will allow greater control on the bending behavior during plasma-jet forming. Use of medium torch speeds and high current input will allow increase in bending rate in less number of passes if melting point is not exceeded. It has also been observed that thermal gradient is a major entity that determined the bending value. Maintaining a large thermal gradient all through the passes has a direct effect on bending and this has been observed in simulation as well as in experiments.

Variation of current input changes the power input from the plasma torch on the metal surface. Increase in power input increases the net heat flux being induced on the sheet metal. Decrease in velocity also increases the heat input on the metal. While high velocities decrease the bending value, lower torch speeds help in increasing the bending angle. This can be attributed to the strain rates and flow stress in the material. Higher velocities result in decrease of surface temperatures and hence thermal gradient. Also strain rates tend to increase when high torch speeds are used. Decrease in surface temperatures and thermal gradient result in increase of flow stress. The effect of strain rates remains undetermined in this simulation. Inclusion of strain rate may not have a predominant effect on bending as the flow stress and surface temperatures on the final bending angle. Slower velocities increase the net heat input on the metal surface as the plasma torch take more time to scan through the sheet. This increase in temperature allows generation of high temperature difference along thickness.

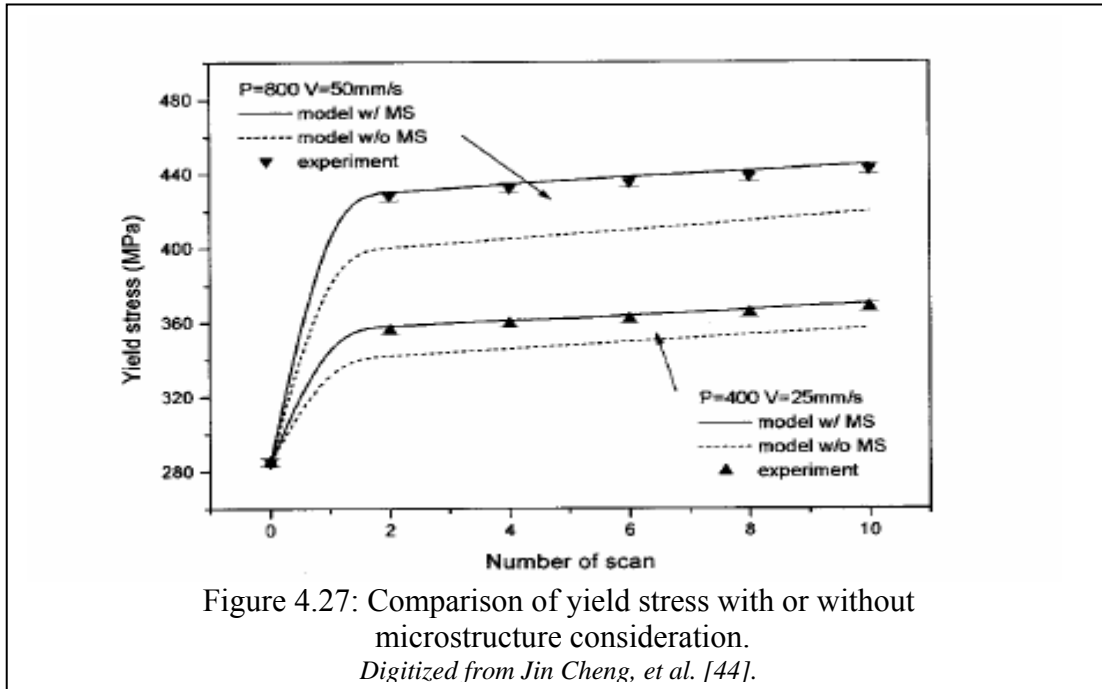
Also high temperatures reduce the flow stress thereby enhancing the bending capability of the material. Thus any residual temperature after cooling in each pass may help increase the bending rate per pass. This can be observed in all the experimental values where bending angle increased significantly after each pass before strain hardening and section thickening hinder the bending rate.



Bending angle depends on the thermal gradient and hence as observed from the Figure above a decrease in thermal gradient decreases the bending angle. The rate of decrease of bending angle with respect to thermal gradient is nonlinear as it also depends on additional parameters such as the temperature dependent thermal and physical properties and the net amount of inelastic deformation. Also, the amount of thermal stresses induced to create necessary plastic deformation varies with change in velocity. This is mainly attributed to the net heat input per unit time and the corresponding effect on the plastic strains being generated.

Multi pass plasma-jet forming requires prediction of the exact material model that can determine the yield stress and other temperature dependent mechanical properties. Yield stress is a vital material property that affects the bending behavior. In a multi-scan forming process, yield strength along the heating zone varies as the material is heated and cooled.

Microstructural changes aided by dynamic recrystallization lead to changes in flow stress and yield stress of the material thus affecting the final bending value [44].



The changes in yield stress and corresponding softening effects need to be taken into account in the material model to obtain accurate measurements in large deformations analysis. Also increase in yield strength increases hardening in the material thereby decreasing the deformation in the sheet metal. The reduction in bending rate after the first pass in the simulation can also be because of elastic recovery during plastic deformation. The material is deformed plastically in the first pass during heating and the stress is then released by cooling. Hence the material ends up with a permanent strain. When the stress is re-applied on the material, it behaves elastically until the new yield point is reached. This new yield point is generally higher than the original yield point.

The elastic strain developed during the reheating process before the material reaches its new yield point results in elastic strain recovery. As a constant load is applied throughout the heating process, thermal stresses and plastic strains to be developed in subsequent passes have to be higher than those preceding them. This can be achieved by determining the material model that fits the yield strength behavior after each pass coupled with use of an efficient cooling method.

Nonlinear thermo-mechanical simulation of plasma-jet forming demands long computational times and high operational memories. Higher the density of the mesh model, greater is the accuracy of the FEM algorithm. A nonlinear model with a moving heat source using a sequentially coupled analysis needs faster processing capability and high disk space to store,

retrieve and execute the data from the results files. Hence all the simulations have been performed on a 4GB RAM dual processor SunFire 280R cluster running on Solaris 9 with parallel processing capability. The system level constraints have been tackled with necessary assumptions to ease the performance and determine required data in a faster manner. Long simulation times and constraints on number of nodes and elements in the University edition of ANSYS led to limiting the analysis only on 0.8mm plates.

While the effect of thermal gradient and its dependency on velocity and current input have been examined, efforts have to be made to study the effects of strain rate and microstructural behavior on yield strength so that modeling of multi pass plasma-jet forming is possible. The effect of strain rate on bending can be examined by altering the velocity and temperature dependent properties such as flow stress. Determining the effect of various cooling methods is also vital for thermal forming processes especially when alternate heating and cooling methods are considered. A parametric analysis with input variables such as velocity, power, cooling method, thickness and orifice diameter needs to be performed to analyze the optimum process constraints in plasma-jet forming process.

CHAPTER V

CONCLUSIONS

5.1 Background

Experimental and Numerical Investigations of Plasma-jet forming have been performed to study the effect of the input variables on the forming efficiency. While thermal conductivity of the material determines the rate of bending, process variables such as current (power) input and velocity of the plasma torch have a major effect on the overall deformation. Scanning method and thickness of the specimen also have a significant effect on the plasma-jet forming process. Key observations from experiments and thermo-mechanical simulation are summarized below.

5.2 Experimental Investigation

The main focus of the experimental investigation was to analyze the effects of changing torch speed and current input on bending. Effect of different scanning methods and effect of changing thickness on thermal bending was also studied.

5.2.1 Factors Affecting Heat Input

- Change in the current input to the plasma torch has a direct effect on bending. Increase in current, increases the net power input and hence the amount of heat flux induced on the top surface of the sheet metal. This increases the surface temperatures and hence the thermal gradient along thickness.

- Changes in the velocity have similar effect on bending as change in current. Increase in the torch speed decreases the bending as the net surface temperatures reduce drastically. This increases the flow stress and also reduces the thermal gradient. While slow torch speeds are used, high surface temperatures are generated as more heat is induced on the surface. Also, variation of torch speed affects the strain rate behavior and hence the final bending angle.

In both the cases above, thermal gradient mechanism has a predominant effect on bending in plasma-jet forming. Hence increasing the thermal gradient along the thickness will allow greater

deformation. Proper coupling of velocity and current input allows enhanced control on the forming process so that higher bending angles can be attained without surface damage or melting.

5.2.2 Factors Affecting Thermal Gradient

Thermal gradient mechanism is mainly prevalent for thin sheets when small beam widths are used. In order to increase the forming efficiency, a large thermal gradient has to be maintained all through the process. Hence to study the thermal gradient behavior different scanning methods were used.

- Use of alternate heating and cooling methods led to higher bending angles in less number of passes as heating, cooling and reheating further in the next pass helps maintain a constant thermal gradient. Bending angle per pass had increased considerably when a double pass method was used and this can be attributed to high surface temperatures being generated. Use of alternate heating and cooling also enhances the material properties by allowing it to regain its structural properties during cooling. While low bending angles were achieved using continuous number of passes, decrease in the bending angle after a few passes was also observed. This is mainly due to strain hardening in the material along the heating width due to large number of plasma scans.
- Thickness of the material used for thermal forming determines the processing time and number of plasma scans needed to obtain the desired bending angle apart from the existing process parameters. Increase in thickness helps increase the temperature difference but not enough stresses are created that lead to plastic deformation. Surface temperatures in a thick sheet are obtained by using high current inputs and lower torch speeds that cannot be used on thin sections. Also as more stresses need to be induced for thick sections use of a larger heating width will help enhance the forming capability.
- Thermal conductivity of the material has a major effect on bending than any other process variable in plasma-jet forming. Experiments involved use of three different materials- stainless steel (SS304), mild steel and magnesium alloy (AZ31). Stainless steel has a very low thermal conductivity and hence high bending values have been recorded. For materials of low thermal conductivity high surface temperatures are generated and these lead to dynamic recrystallization of the material especially in stainless steels [26]. AZ31 alloy has higher thermal conductivity

than mild steel but higher bending values have been observed. This may be due to fine grained structure of the magnesium alloy specimen used.

Experimental investigation formed a basis to study the processing effects on bending where thermal gradient was the major factor. To analyze the effect of these process variables numerical simulation has been performed and the results have been validated with some of the experimental observations.

5.3 Numerical Simulation

The sequentially coupled thermo-mechanical analysis was performed mainly to study the temperature field distribution and predict the bending behavior. Efforts have also been made to correlate bending with thermal gradient. Simulation was performed by using different scanning methods on SS304 sheets of 0.8mm thickness. The transient thermal and structural analysis was simulated with geometrical and material nonlinearities in consideration. Temperature dependent material properties have been used for analysis.

The following observations have been made based on the thermo-mechanical simulation performed.

1. The surface temperatures are maximum when low torch speeds and high current inputs are used. Thermal gradient along the thickness is high when the temperatures on the top surface are maximum.
2. A constant peak temperature below the melting point can be obtained by using a combination of velocity and current.
3. Thermal gradient decreases as the number of passes increase when continuous scanning option is used. A constant and large temperature difference can be maintained using a double pass method.
4. The temperature distribution on the surface are symmetrical along the center line (neutral axis) of the heating width.
5. Temperatures are maximum on the top surface and decrease through the thickness because of the use of coolant on the bottom surface.
6. The heat flux induced temperatures are localized and are found to be maximum at the center of the heating width and decreases as we move away from the neutral axis.
7. Residual stresses at the end of the forming process were found to be minimum.

8. A decrease in thermal gradient along thickness leads to a significant decrease in bending angle.
9. Thermal and mechanical stresses are maximum in the heating width and constitute the major part of the deformation mechanism.
10. The planar stresses on the sheet are symmetrical about the centerline along the heating width and the effect of clamping on one side was negligible. Also no local variation of these stresses was found during multipass bending.
11. Increase in temperature reduces flow stress and assists bending while increase in hardness and yield strength reduces bending.
12. Bending angle reduces with decrease in velocity and also with reduction in current input.
13. Elastic recovery and change in yield strength after every plasma scan lead to variation in bending angle. Hence a material model that can predict the temperature dependent material properties after various plasma irradiations is required to achieve accurate results during multipass bending.

CHAPTER VI

RECOMMENDATIONS FOR FUTURE WORK

Most of the present day research in the field of thermal forming is on laser forming. Lasers have an advantage of precision and accuracy while plasma heat sources are economical and efficient and repeatable. Plasma-jet forming being cheaper needs to be further improved to avail enhanced control of the process.

6.1 Improvements In Numerical Modeling

Computational modeling involving finite element analysis can improve day by day because of vast improvements in commercial FEM codes. Thermo-mechanical simulation used in current dissertation does not avail adaptive remeshing and rezoning capability. Present day FEM codes provide rezoning and adaptive remeshing only for 2-D analysis. Rezoning and remeshing help in improving the geometrical and mesh structure dynamically there by increasing the accuracy of the FEM. Use of these capabilities in 3-D thermo-structural analysis reduces the deformation error and helps maintain reasonable aspect ratio values.

Study of the effect of input variables such as offset distance, orifice diameter and cooling rate is also necessary. Cooling rate and torch speed affect the strain rate during the process and thus affects the overall deformation rate. Therefore, proper coupling of all the process variables will allow enhanced control on the forming parameters and thereby provide with optimum deformation characteristics.

Strain rates have been assumed to be constant in the present analysis. Investigation of the effect of strain rate with change in temperature and velocities has to be considered especially in metals where recrystallization and phase transformation have been observed. Strain rate also affects the flow stress of the material during metal forming. Hence study of strain rate effects using numerical simulation needs to be done to validate its observations with metallurgical analysis. Metallurgical analysis should involve tensile tests to study the yield strength and hardness of the heating width where deformation is maximum. These tests have to be done in specimens after

each pass so as to determine the net effect of multiple plasma scans on the yield strength of the material.

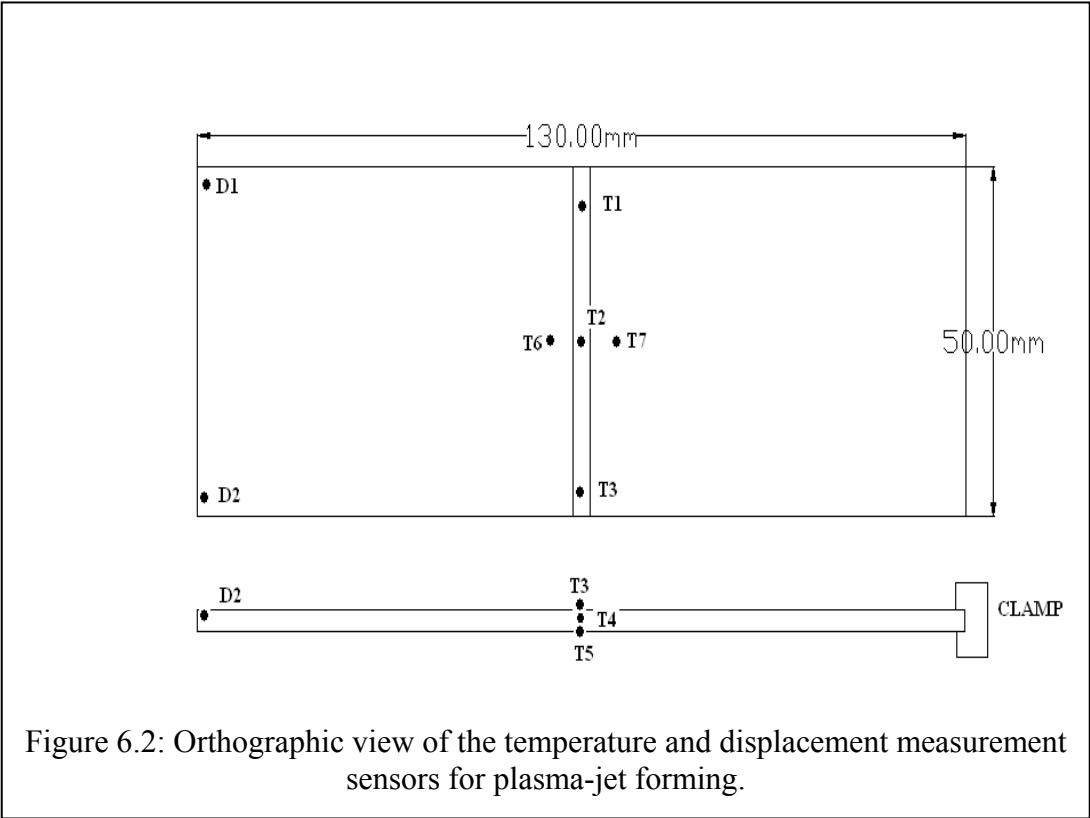
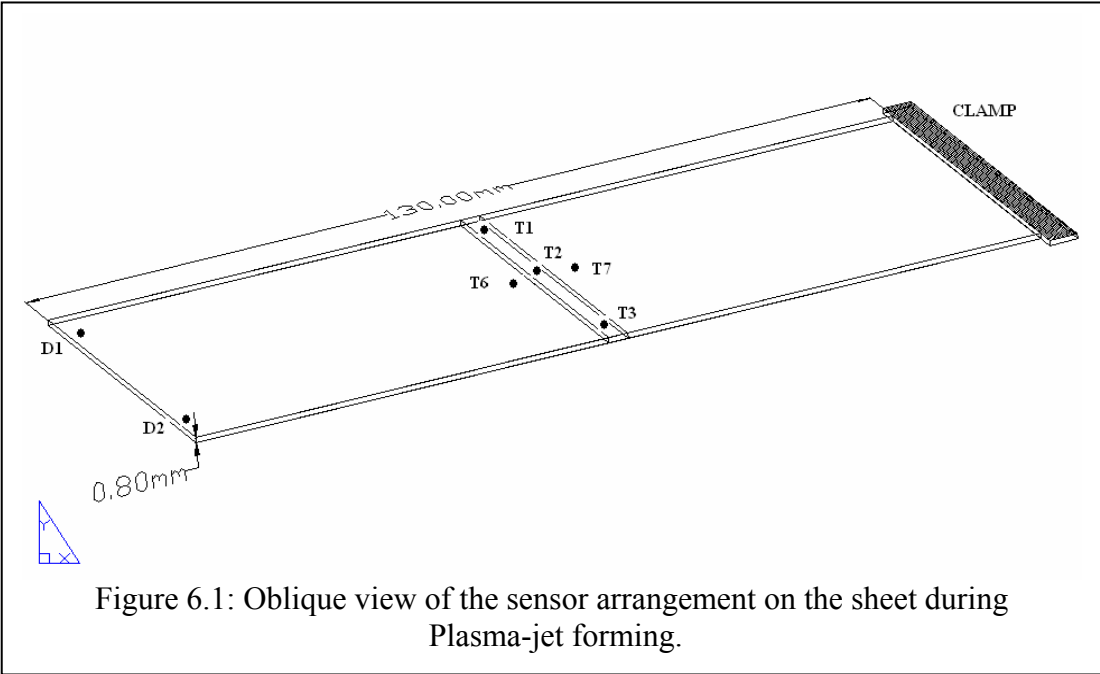
Also, any change in the input variable will affect the yield strength. Metallurgical analysis is also important to resolve the material model irregularities for simulation of multipass plasma-jet forming as the behavior of yield strength, flow strength and hardness can be predicted.

The present thermo-mechanical analysis can be extended further to couple with fluid analysis to study the material flow behavior during plastic deformation.

Also a parametric analysis with current, velocity and heating width as variables can be performed to optimize the bending behavior. Also the thermo-structural analysis can further be improved to study the effects of different cooling methods and Gaussian heat distribution model. This can be further applied to simulate models for other materials such as mild steel, aluminum, copper and magnesium alloys. Also effect of varying thickness and cooling effects can be examined using a parametric study.

6.2 Improvements In The Control System

Accuracy and repeatability are the two major factors that determine the consistency of a system. Plasma-jet forming system can be improved by using closed loop controls to enhance the forming capabilities. Current plasma-jet forming apparatus is a semi-automatic forming system where the motion and position controls are highly efficient. This system can be extended to automate the feedback process so that rapid changes in temperatures and bending angles can be recorded. Plasma-jet forming system requires feedback systems that are highly sensitive to minute changes in surface temperatures and deformation. To enhance this capability a futuristic model is developed based that can be used with the current system.



The arrangement of the sensors has been suggested for sheets of dimension (130×50×0.8) mm. The sensors T1-T7 represent thermocouples used to measure temperature on the sheet during plasma-jet forming. D1 & D2 represent displacement sensors. The displacement sensors can be dial gauges or linear variable displacement transducers (LVDT). Measurement of deflection on the plate can be done on the two ends (D1 & D2). Any major difference in the measurements on sensors D1 & D2 will be an error in clamping or experimental setup.

Rapid changes of temperature occur along the heating width as the moving heat source scans through the plate. Measurement of temperatures at various points on the heat affected zone is necessary to study the temperature field distribution. Temperatures measured on the top surface and along the thickness will also help in validating the results obtained from numerical simulation. While highly sensitive thermocouples can be used to measure temperatures, infrared thermal sensing cameras can also be utilized.

The temperatures during the plasma scans can be recorded with a charge coupled device camera equipped with infrared filters after calibrating the camera sensor and image processing, the temperature distribution along the heating width can be determined. Also the temperature history can be recorded during the plasma-jet forming process by 36 gauge K type thermocouples at seven locations on the top and bottom surfaces along the transverse sections near the middle of the plate.

Feedback from these sensors will require additional data acquisition boards so that computer control on the measurements is possible. Plasma torch has been manually adjusted during experiments so that the line of heating is normal to the plasma beam. Automation of the control system will require programming the motor connected to the plasma torch swivel and improve accuracy of plasma-jet forming. This also requires prediction of the bending angle after each pass so that the plasma torch can be moved accordingly and perpendicularity is maintained between the plasma beam and the metal plate.

Experiments have to be performed on sheets of thickness greater than 2mm to determine the effect of thickness on bending angle and the flexibility of the system on the whole. These should also involve specimens of varying width as greater width as change in the width will change the time involved in heating by the plasma torch. Experiments must be further extended to other materials so that complex shapes can be easily formed. It was observed that higher current inputs coupled with lower torch speeds and different scanning method helped in increasing the bending

for thick sheets. The flexibility of this process for sheets of greater thickness (up to 8mm) needs to be examined further.

The effect of gas flow rate, offset distance and heating width has not been considered in the present dissertation. A detailed analysis of these parameters will help improve the process as a whole. Also, the parameters affecting the heat input have to be studied further to determine possible relation between the heat output from the plasma torch based on current input given and its subsequent effect on surface temperatures.

The plasma-jet forming method is a flexible forming process that provides an economical means of bending sheet metals. Plasma-jet forming is highly efficient process and proper coupling of the process parameters will further enhance the possibilities of increasing the bending rate per pass.

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APPENDIX

APPENDIX-A

NOMENCLATURE

L	Offset Distance (mm).
W	Plasma torch orifice Diameter (mm).
t	Thickness of the sheet metal (mm).
V	Velocity of the plasma torch (mm/s).
I	Current (A).
ρ	Density (Kg/m ³).
c	Specific Heat capacity (KJ/Kg-K).
v	Velocity of the moving heat source (m/s).
v_x	Velocity of the moving point source. in x-direction (m/s).
T	Temperature (K).
T_o	Ambient Temperature (K).
k	Thermal Conductivity (W/mK).
k_x, k_y, k_z	Thermal Conductivity in x ,y and z direction (W/mK).
ξ	Distance of the point heat source from a fixed reference point(m).
q	Heat input from the plasma source(J/m).

K_0	Bessel function of the first kind, zero order.
R	$(\xi^2+y^2+z^2)^{1/2}$, Distance from the plasma heat source to particular fixed point.
α	Thermal Diffusivity (m^2/s).
f	Heat transfer coefficient.
t	Time(sec).
σ	True Stress(Mpa)
ε	Total Strain.
Y	Elastic(Young's) Modulus(N/m^2).
E	Voltage (V).

APPENDIX-B

The ANSYS code has been executed in batch mode on a UNIX environment to reduce the operational time and other system constraints.

The following command executes the program on a UNIX server in batch mode.

```
nohup ansys100 -b -p <inputfilename> & outputfilename &
```

The ANSYS program for a single plasma scan using SS304 of 0.8mm thickness and speed 8mm/s is given below. The variables in the do loop can be altered to increase the number of passes and alter the process parameters.

```
/com,thermal                ! Start Thermal Analysis
/FILNAME,plasma,0
/TITLE,SS304...8mm/s....0.8mm Thickness
/PREP7
ET,1,SOLID90                ! Selection of element type
/units,si
type,1
mat,1
mp,emis,1,0.96
mptemp,1,300,500,900,
mpdata,kxx,1,1,16.5,17.5,18.8    ! Defining Temp. Dependent Thermal
                                Properties
mpdata,dens,1,1,7900,7850,7800
K,1,-.065,0.025,,
K,2,-0.065,-0.025,,
K,3,0.065,-0.025,,
K,4,0.065,0.025,,
K,5,-.001,0.025,,
K,6,-0.001,-0.025,,
K,7,0.001,-0.025,,
```

K,8,0.001,0.025,,

LSTR, 1, 2

LSTR, 2, 6

LSTR, 6, 5

LSTR, 5, 1

LSTR, 5, 8

LSTR, 8, 7

LSTR, 7, 6

LSTR, 7, 3

LSTR, 3, 4

LSTR, 4, 8

FLST,2,4,4

FITEM,2,1

FITEM,2,4

FITEM,2,3

FITEM,2,2

AL,P51X

FLST,2,4,4

FITEM,2,3

FITEM,2,5

FITEM,2,6

FITEM,2,7

AL,P51X

FLST,2,4,4

FITEM,2,6

FITEM,2,10

FITEM,2,9

FITEM,2,8

AL,P51X

```
VOFFST,1,.0008, ,
VOFFST,2,-0.0008, ,
VOFFST,3,0.0008, ,
```

```
vglue,1,2,3
```

! Generation of Geometrical Model

```
FLST,5,1,4,ORDE,1
```

```
FITEM,5,3
```

```
CM,_Y,LINE
```

```
LSEL, , , ,P51X
```

```
CM,_Y1,LINE
```

```
CMSEL,,_Y
```

```
LESIZE,_Y1, , ,50, , , , ,1
```

```
FLST,5,1,4,ORDE,1
```

```
FITEM,5,5
```

```
CM,_Y,LINE
```

```
LSEL, , , ,P51X
```

```
CM,_Y1,LINE
```

```
CMSEL,,_Y
```

```
LESIZE,_Y1, , ,5, , , , ,1
```

```
FLST,5,1,4,ORDE,1
```

```
FITEM,5,25
```

```
CM,_Y,LINE
```

```
LSEL, , , ,P51X
```

```
CM,_Y1,LINE
```

```
CMSEL,,_Y
```

```
LESIZE,_Y1, , ,5, , , , ,1
```

```
MSHAPE,1,3D
```

```
MSHKEY,0
```

```
CM,_Y,VOLU
VSEL, , , , 4
CM,_Y1,VOLU
CHKMSH,'VOLU'
CMSEL,S,_Y
VSWEEP,_Y1
```

```
CMDELE,_Y
CMDELE,_Y1
CMDELE,_Y2
CM,_Y,VOLU
VSEL, , , , 5
CM,_Y1,VOLU
CHKMSH,'VOLU'
CMSEL,S,_Y
VMESH,_Y1
CMDELE,_Y
CMDELE,_Y1
CMDELE,_Y2
CM,_Y,VOLU
VSEL, , , , 1
CM,_Y1,VOLU
CHKMSH,'VOLU'
CMSEL,S,_Y
VMESH,_Y1
CMDELE,_Y
CMDELE,_Y1
CMDELE,_Y2
asel,s,,,1,6,1
nsla
```

! Mesh Model

```

sf,all,conv,2,300
allsel
asel,s,,19,24,1
nsla
sf,all,conv,2,300
allsel
asel,s,,8,
nsla
sf,all,conv,2,300
allsel
asel,s,,17,
nsla
sf,all,conv,2,300
allsel
FINISH
/SOLU
antype,trans
trnopt,full
nropt,auto,,
eqslv,
solcontrol,on
neqit,on
autots,on
outpr,all,all
tunif,300
kbc,0
outres,basic,all,,
outres,epel,all,,
outres,eppl,all,,

```

! Boundary conditions

! Ambient Conditions

! Natural Convection

! Start Transient Analysis

! Newton Raphson Optimization

!Initial Condition

!Ramped Solution

```

outres,epth,all,,
*set,k,1 !Heating Phase
*set,j,0.000001
*set,i,5
*do,k,1,2,1 ! No. of Passes, One pass equals 2 iterations

*if,i,eq,5,then
*do,i,5,230,5 ! Forward Iteration
!deltim,0.068,0.068,0.068,
time,j
deltim,0.068,0.068,0.068,
sfdele,all,hflux
esel,s,,i
nsle,s,face,6
sf,all,hflux,16800000 !Moving Heat source heat flux application surface load on
! nodes of element surface

allsel
esel,s,,i+230
nsle,s,face,6
sf,all,hflux,16800000
allsel
esel,s,,i+460
nsle,s,face,6
sf,all,hflux,16800000
allsel
esel,s,,i+690
nsle,s,face,6
sf,all,hflux,16800000
allsel
esel,s,,i+920

```



```
nsle,s,face,6
sf,all,hflux,16800000
allsel
esel,s,,i-4
nsle,s,face,1
sf,all,conv,3,278
```

! Coolant on the bottom

```
allsel
esel,s,,i+226
nsle,s,face,1
sf,all,conv,3,278
```

!Convection on Bottom Surface

```
allsel
esel,s,,i+456
nsle,s,face,1
sf,all,conv,3,278
```

```
allsel
esel,s,,i+686
nsle,s,face,1
sf,all,conv,3,278
```

```
allsel
esel,s,,i+916
nsle,s,face,1
sf,all,conv,3,278
```

```
allsel
solve
esel,s,,i
esel,a,,i+230
esel,a,,i+460
esel,a,,i+690
esel,a,,i+920
```

```
nsle,s,face,6
sfdele,all,hflux          ! Deletion of Surface loads on previous
                           elements
```

```
allsel
*SET,j,j+0.136
*enddo
sfdele,all,hflux
*elseif,i,eq,230,then
*do,i,230,5,-5           ! Backward Iteration
```

```
time,j
deltim,0.068,0.068,0.068,
esel,s,,i
nsle,s,face,6
sf,all,hflux,16800000
allsel
esel,s,,i+230
nsle,s,face,6
sf,all,hflux,16800000
allsel
esel,s,,i+460
nsle,s,face,6
sf,all,hflux,16800000
allsel
esel,s,,i+690
nsle,s,face,6
sf,all,hflux,16800000
allsel
esel,s,,i+920
```

```
nsle,s,face,6
sf,all,hflux,16800000
allsel
esel,s,,i-4
nsle,s,face,1
sf,all,conv,3,278
allsel
esel,s,,i+226
nsle,s,face,1
sf,all,conv,3,278
allsel
esel,s,,i+456
nsle,s,face,1
sf,all,conv,3,278
allsel
esel,s,,i+686
nsle,s,face,1
sf,all,conv,3,278
allsel
esel,s,,i+916
nsle,s,face,1
sf,all,conv,3,278
allsel
solve
esel,s,,i
esel,a,,i+230
esel,a,,i+460
esel,a,,i+690
esel,a,,i+920
nsle,s,face,6
sfdele,all,hflux
```

```

allsel
*SET,j,j+.136
*enddo
sfdele,all,hflux
*endif
*set,k,k+1
*enddo
sfdele,all,all           ! End of 2 plasma scans
time,50
deltim,1,1,1
asel,s,,1,6,1
nsla
sf,all,conv,2,300       ! Cooling Phase
allsel
asel,s,,19,24,1
nsla
sf,all,conv,2,300       !Natural Cooling at Ambient Conditions
allsel
asel,s,,8,
nsla
sf,all,conv,2,300
allsel
asel,s,,17,
nsla
sf,all,conv,2,300
allsel
solve
sfdele,all,all
asel,s,,1,6,1
nsla
sf,all,conv,2,300       ! Resetting Boundary Conditions

```

```

allsel
asel,s,,19,24,1
nsla
sf,all,conv,2,300
allsel
asel,s,,8,
nsla
sf,all,conv,2,300
allsel
asel,s,,17,
nsla
sf,all,conv,2,300
allsel
save,plasma,dbt

```

! Save Thermal database
! END OF THERMAL ANALYSIS.

```

/PREP7
ETCHG,TTS
mp,prxy,1,0.3
mp,alpx,1,12e-6
mpTEMP,1,300,900,
mpdata,ex,1,1,17.9E10,14.96E10,
TB,KINH,1,2,8
TBTEMP,300
! Strain, stress at temperature = 300K
TBPT,,11e-4,197e6
TBPT,,5E-3,283e6
TBPT,,10E-3,433e6
TBPT,,15E-3,508e6
TBPT,,20E-3,433e6
TBPT,,25E-3,423e6

```

! Start Structural Analysis
! Switch Element Type Thermal to Structural
! Define temperature-dependent physical properties
! Activate a data table
! Kinematic Hardening Material Model

```

TBPT,,30E-3,415e6
TBPT,,35E-3,409e6
TBTEMP,900                                !Temperature = 900K
TBPT,,.00125,187e6
TBPT,,.0045,301e6
TBPT,,.012,411e6
TBPT,,.016,487e6
TBPT,,.023,418e6
TBPT,,.0275,405e6
TBPT,,.032,402e6
TBPT,,.037,400e6
/XRANGE,0,0.005
TBPLOT,KINH,1
finish
/SOLU
lsclear,all
antype,trans,new                          ! Start Transient Analysis
autots,on
neqit,1000
nlgeom,on                                  ! Large Deflection Analysis
outpr,all,all
outres,all,all,,
kbc,0
nsubst,26,1000,1
timint,off
time,0.0001
ASEL,S,, , 5
NSLA
D,ALL,, , , , ,ALL,, , , , ,
ALLSEL,ALL
lswrite,1

```

```

timint,on

*set,n,2
*set,v,0.136                                ! Heating Phase
*do,v,0.136,12.512,0.136                    ! Forward & Backward Iteration
deltim,0.068,0.068,0.068
time,v
LDREAD,TEMP,,v,, 'plasma', 'rth',          !Reads Thermal Data As Structural Body Loads
lswrite,n
*set,n,n+1
*enddo
deltim,1,1,1
time,50                                      ! Cooling Phase
LDREAD,TEMP,,50,, 'plasma', 'rth',
lswrite,94                                  ! Write Load Steps
lssolve,1,94,1                              ! Solve all load steps
                                           ! End of Single Pass
save,plasma,dbs                             ! Save Structural Database
save                                         ! Save all
                                           ! END OF SIMULATION.

```

VITA

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- July 22, 1983 at Hyderabad, Andhra Pradesh, INDIA.

Education

- Bachelor's degree in Mechanical Engineering (B.Tech),
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