JIMMA UNIVERSITY

SCHOOL OF POST GRADUATE STUDIES

JIMMA INSTITUTE OF TECHNOLOGY

FUCALTY OF MECHANICAL ENGINEERING,

MANUFACTURNG SYSTEM ENGINEERING STREAM

Modeling of Plastic Deformation Mild Steel Bloom ASTM [A36] Under Hot Rolling Mills

A Research Submitted to the School of Graduate Studies Jimma University, Jimma Institute Technology (JIT), in Partial Fulfillment of the Requirement for Degree of Master of Science in Mechanical Engineering (Manufacturing System Engineering Stream).

By: Wakuma Disasa

Advisor: Ass.Prof.Dr. Mesay Alemu

February, 2022

Jimma Ethiopia

APPROVAL

Master's Program Final Thesis Acceptance Approval Form

This is to certify that thesis prepared by Wakuma Disasa entitled: Modeling of Plastic Deformation Mild Steel Bloom ASTM [A36] Under Hot Rolling Mills and submitted in partial fulfillment of the requirement for the degree of master of science in manufacturing system engineering complies with the Jimma university and meets the accepted standards with respect to originality and quality.

Approved by Board of Examiners:

External examiner	*Signature*	*Date*
Asst. Prof. Dr.Desalegn Wegaso	________________	________________
Internal examiner	*Signature*	*Date*
Ahamed Jemal (Msc)	________________	________________
Advisor	*Signature*	*Date*
Ass.Prof. Dr.Mesay Alemu	________________	________________
Stream Chairman,	*Signature*	*Date*
Hana Beyene (Msc)	________________	________________

DECLARATION

I declare that the work in this thesis was carried out with the requirements of the University's regulations and that it has not been submitted for any other academic reward to any

University. I certify that, to the best of my knowledge, my thesis does not infringe anyone's copy right nor violate any upon proprietary right, and that any ideas, techniques, quotations and any other material from the work of other people included in my thesis published or otherwise, are fully acknowledged in accordance with the standard referencing practices.

Name	*Signature*	*Date*
Wakuma Disasa	____________________	____________________

This is to certify that the above declared made by the candidate is correct to the best of my knowledge.

Principal Advisor:	*Signature*	*Date*
Ass. Prof. Dr.Mesay Alemu	____________________	____________________

ACKNOWLEDGEMENT

I would like to thanks first the almighty GOD for giving me this opportunity and the omnipresent for giving me strength in all the critical situations and supporting me spiritually throughout my life.

First of all, I would like to acknowledge my indebtedness and render my warmest thanks to my Advisor Ass .Prof. Dr. Mesay Alemu (PhD) who made this work possible. His friendly guidance and expert advice have been invaluable throughout all stages of the work. In particular, I express my deep regards to my staff members, colleagues for their support and shared materials and ideas throughout the completion of this thesis. I extend my deep sense gratitude to them first for their valuable guidance, inspiring discussions, constant encouragement & kind co-operation throughout period for all the thoughtful and mind stimulating discussions we had, which prompted us to think beyond the obvious and I have enjoyed their companionship so much during my stay at Jimma Institute of Technology (JIT) especially faculty of mechanical engineering manufacturing system engineering stream chairman Hana Beyene and other staff for their invaluable guidance, motivation, constant inspiration and above all for their ever co-operating attitude that enabled me in bringing up this thesis in the present form.

ABSTRACT

To predict the distribution of stress and strain fields in hot rolling process the computer models were built using thermo-mechanical coupling rigid-plastic FEM. In metalworking, rolling *has been analysis of strain-stress and temperature states during hot rolling process for bloom in which metal stock is passed through a two high stand Pair of rolls. This work studied the effect of rolling parameters at different rolling temperatures, on the mechanical properties of hot-rolled mild steel. It's a technique in which a material having relatively large thickness geometry is plastically deformed in one or more sequential operations and transformed into a useful part, without change in the mass or composition of the material***.*** *Plastic deformation, finite element method, the hot rolling process is simulated and analyzed. The rollers and bloom are represented by respectively rigid and deformable bodies, and 3D models were developed for both. This thesis was carried out to study the rolling within the hot rolling aiming to evaluate 3D FEA and thermo-mechanical boundary condition subsequent saw change on the bloom thickness during deformation process.*

The applied conditions are extremely important in order to achieve the desired quality product. Successful hot rolling would be dominated by calculating the effect of some important parameters on the work piece during the deformation processes. In this thesis the hot rolling would be carried out to predict effects of temperature on the strain and stress distribution would be discussed in detail using the finite element method application. The model would be developed by considering all of the non-linearity of material, geometric, boundary, and heat transfer that present in the rolling processes. This simulation results are verified by the experimental data of stress vs. Strain curve. In this paper, the analysis of the 3D strain state for the hot rolling process of bloom mild steel with the application of the finite element method is presented. The results of work connected with the simulation of metal flow scheme, and fields of stress, strain and temperature in the material deformation process in the rolling conditions are presented. The distribution of the effective strain, the stress on the surface of rolling cross sections is determined. Rolling speed is an important parameter for hot rolling, since this factor directly controls the strain rate, flow stress, heat of deformation and heat transfer coefficient. Rolling speed is a variable that it has great effect on heat transfer, flow stress, meshing size.

KEY WORDS: *Hot rolling process simulation, thermo-mechanical, finite element analysis. bloom, 3D model, roller speed, rolling process, single roll pass stand, hot rolling, stress state, temperature.*

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABBREVIATION/LIST OF SYMBOLS/NOMENCLATURE

ASTM: American standard test machine

FEA: Finite element analysis

FEM: Finite element methods/model

GNL: Geometric nonlinearity

BNL: Boundary condition nonlinearity

MNL: Material nonlinearity

K: Thermal conductivity

ρ: Material density

$\mathcal{E}_{ij}$: Component of stress tensor

A /F: Cross Sectional Area (m2)

A_{rad} : Area of radiating surface (m2)

Ą: Contact Area

Ǩ: Stiffness matrix (N/m)

Ć Heat capacity matrix (W/m^2K)

C_p: Specific Heat (J/kg K)

C: Steel's carbon content (weight per cent)

ε_{ij} : Effective strain rate tensor (s^{-1})

E: Young's modulus of elasticity (MPa)

È: Lagrangian strain tensor

E_{ij}: Components of the strain tensor in

S_{in}: Rate at which thermal energy enter through the control surface (W/m^3)

S_{out}: Rate at which thermal energy enter through the control surface (W/m^3)

$\dot{S}_{st}$: Rate of energy stored within the control volume (W/m^3)

$\hat{S}_{St}$:Energy stored flux (W/m^2)

S: Work function for rigid plastic materials

F: Roll force (N)

F: Nodal Forces matrix (N)

F_s: Contact separation force

F_t :Tangential Force (N)

F_n: Normal Reaction (N)

G: Shear modulus (MPa)

K: Stiffness matrix (N/m)

K_c: Heat Conduction matrix (W/m^2K)

K: Strain hardening coefficient

K: Shear yield stress (MPa)

K: Thermal conductivity/ conduction heat transfer coefficient (W/m2K)

K: Boltzmann constant=1.380 x 10-23J/K molecule

M: mass of rolled stock, work piece, bloom, etc (kg)

n :Strain hardening exponent

n̄ :Unit normal vector

P: Roll pressure (MPa)

P: Hydrostatic pressure tensor (MPa)

q_{fr} : Heat transfer rate due to friction (W)

q''_{cond} : Conduction heat flux (W/m^2)

q''_{conv}: Convection heat flux (W/m^2)

q''_{rad} : Radiation heat flux (W/m^2)

q''_{pw}: Plastic work heat generation flux (W/m^2)

q_{fr}: Friction heat flux (W/m^2)

$\dot{q}$: Rate of heat generation per unit volume (W/m^3)

S_{ij}: Components of the deviatoric stress tensor (MPa)

h_0/h_1 :Bloom/work piece entry thickness (m

h_f/h_2 : Bloom/work piece exit thickness (m)

h_a : Average work piece thickness (m)

Δh : Draft (m)

L_{pw}: Length of region subject to plastic deformation

L: Roll gap/contact arc length (m)

Q: Heat Flux Vector (nodal) (W/m^2K)

R: Roll Radius (m)

S: Deviatoric Stress Tensor (MPa)

S: Constrained yield strength in rolling (MPa)

$S_{\bar{F}}$: Surface where traction $\bar{F}_i$ is prescribed

$S_{\bar{v}}$: Surface where velocity $\overline{F}_i$ is prescribed

T: Cauchy Stress Tensor (MPa)

T: Nodal temperatures matrix (K)

T_R: Roll temperature (K)

T_W: Work piece temperature (K)

T_∞:Environment temperature (K)

V_r: Roll surface velocity (m/s)

V: Volume (m3)

V_o: Work piece initial speed (m/s)

V_f:Work piece exit speed (m/s)

V: Velocity vector (m/s)

V_x:Velocity of the metal being rolled at section dx (m/s)

Δv: Increment of nodal velocity

V_r : Work piece-roller sliding velocity

Γ_i: Mechanical boundary conditions corresponding to boundary i

$\Phi_{i:}$Thermal boundary conditions corresponding to boundary i

α: Roll bite angle (rad)

σ :Stephan-Boltzmann constant = 5.67 x 10-8W/m^2K^4

CHAPTER ONE

INTRODUCTION

1.1 Background of the study

Metal Forming processes are defined that some of manufacturing processes to change the metal from one shape to another shape without changing in mass or chemical composition, so the metal surface which required to forming is in tangent with the roller [1]. Rolling is one of the most common method used in the plastic deforming metals into suitable shapes for more wide range products today and it is typically the first metal working process after casting [2]. Almost metal forming processes are employed in industries which represents the first forming operation after melting and the process is carried out at the rolling temperature, allowing to achieve large shape variations in the manufactured item, thus perform high deformations [3].It is one of the most common popular processes in manufacturing industries in that almost 80% of metallic equipment has been exposed to rolling, at least one time in their production period [1,2].The study of metal forming processes has been carried out by means of several approaches, based on the mechanics analysis. However it is necessary to observe that thermal-mechanical analysis allows to examine the problem in its complexity and analysis the effect of temperature which depends on the variation exist in heat transfer between the bloom and the environment and heat generation due to the conversion of the heat to energy. Subsequently the thermo- mechanical properties of the rolled metal are updated on the basis of the temperatures, thus allowing a more description of the process. In metal forming as it is well known it is possible to achieve higher values of the reduction in thickness in a single pass. consequently, when bloom geometry hot rolled, the thermal-mechanical coupled must be analyzed in order to improve the predictive of the simulation result [3] and analysis in the deformation process is necessary to properly understand the properties of work piece and the effects of different parameters and to simulate such a process. A number of metals have been exhibit rate (time) dependent plastic behavior at high temperatures. The flow of metals at a high temperature, enhances the desirability of an appropriate rate dependent plastic material model for analysis [5]. In metal working, dimension and shape [6] of metal stock geometry changes due to of pressure applied by cylindrical rolls during the operation [4,5]. The rolling process involves both material non-linearity and geometry non-linearity. Moreover, non-linearity of heat boundary can exist as a result of heat radiation between the work piece and the surroundings [8].Rolling has been more widely applied for high productivity as compared with other metal forming processes. Steel is the largest consumption metal materials [9].In industrial countries out of all varieties of the rolling processes about 40-60% products are produced within the flat rolling [5,6,10]. Nowadays, almost 90% of the steel is rolled into different section and so on while bloom is backbone or the key raw materials for steel products and the high quality of prerequisite for high performance rolled products, and it called as a "universal steel" and in recent years widely used in economic departments as major products [3,5].Being the most prominent all metal forming operations, rolling has received extensive consideration for the past decades. During recent years, modeling and simulation of this process along with the prediction of the rolled products properties have been extensively conducted with special attention drawn toward the use of FEA. FE studies have mostly been performed in order to investigate the deformation and thermal behavior of the hot rolling processes. The processes have also gained great attention in several works since it simplify the prediction of temperature, strain and stress distributions in the bloom material, because these variables control the final microstructure and mechanical properties of the rolled product [12].Metal forming is the area of metallurgy which is concerned with conversion of metal casting ingot or bloom, billet, slab into more useful shape such as flat plate, rod, bar and sheet metal with important analysis without changing in mass or chemical composition, so the metal surface which required to forming is in tangent with the roller[1]. Plastic deformation of a metal means shaping of metals into different shape products while the term of plastic deformation describes permanent [1] shape change, in contrast to elastic deformation. Rolling is a common which plays an important role in the process of various compositions of steels ranging from low carbon to highly alloyed stainless steels and manufacturing companies producing metals supply in form of ingots which are obtained by casting liquid metal and obtained slab, billets, blooms which are soaked at high temperatures (1100 to 1300°C) [11,12] and then progressed to plate, bars and sheet [14].From the different metal forming process, reducing the thickness or changing the cross-section of a work piece by compressive forces applied through a set of rolls that revolve, the space between the rolls being less than the thickness of the entering work piece is accomplished by passing the material to be rolled between revolving roller at the same speed but in opposite direction [4,5].

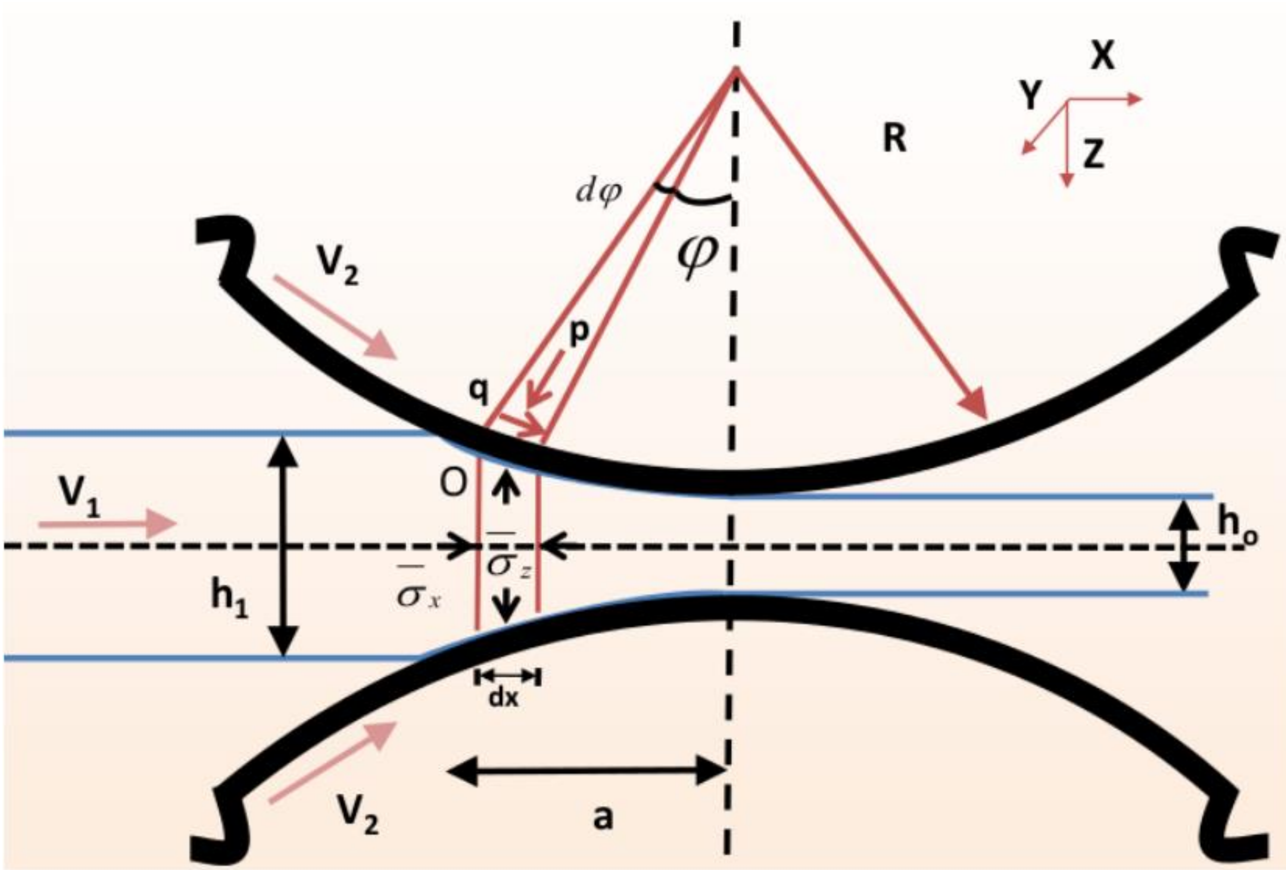


Figure1. 1: Rigid-perfectly plastic rolling scheme for flat rolling.

Metal forming functions is the generation of product geometry with mechanical properties by repeatedly compressing the hot metal [13,15] between roller**.** It basically involves pushing a metal work piece into the gap between two rotating rolls, which then simultaneously draw the work piece into the gap between rolls and compress it to reduce the thickness and increase the length [17]. Modern rolling mills are extremely efficient units capable of processing over a million tons of metal per year. Today there are a lot of different mill setups available. The two-high reversible mill is however widely used and one of the most common for rolling of large products likes blooms [18]. A reversible rolling mill is often used for the first stages of large sections such as ingots, bloom and slabs to reduce their thickness as rapidly as possible. Further reductions are achieved in a series of one-way mills known as ‘stands. Depending on the basis of temperature, rolling process can be divided as hot (when the rolling temperature exceeds the re-crystallization temperature of the work piece) and cold (deformation is imparted to the feedstock below its re-crystallization temperature) rolling [18,19, 20]. Because of the complex nature of rolling mill roll the available methods and conditions of their application is extremely important in order to achieve high quality of products. Simulation and modeling of roughing first pass deformation of bloom of mild steel rolling mill analyses. Metal forming process can be defined as a constant process of plastic deformation for long parts of stable cross section, in which a reduction of the cross-sectional area is achieved [6]. The major development in industry metal forming process has been transformed to the application of finite element method simplify the solution of complicated non-linear metal deformation processes. The numerical analysis procedure used to obtain approximate solutions to boundary value problems, which are found in every field of engineering. The problems with closed form solutions that can be exist in any textbook on strength of materials, fluid dynamics, and other fields of mechanics, correspond to usually rather basic models of reality, where a lot of simplifying assumptions in order to be able to solve the differential equations and their associated initial boundary conditions, that are generated when formulated. The finite element method became an indispensable tool in the field of engineering mechanics [19] to solve many complex structural mechanics, heat transfer analysis, and fluid mechanics problems and it was initially applied to the structural analysis and expanded to the thermal. In the world of engineering finite element method is one of the most widely used in the metal forming and stress and deformation analysis in the fields of building structures, bridges, aviation, automotive, and there is fluid flow analysis, heat transfer and other non-structural problems[17].The FE technique has been used as a tool in the modeling of metal forming and found a wide application in this area, in particular, in the hot rolling industries. The principal goal of rolling simulation is to connect the process variables, such as the rolling speed, rolling temperature, rolling stand geometry, strain, and stress field in the bloom. By FE method, the hot rolling bloom deformation behavior, including the rolling speed and the stress- strain distribution was investigated with different temperature value were analyzed [20]. The models of the roller and the bloom are developed to investigate the effect of different process parameters such as initial rolling temperature, strain and effective stress distribution.

1.2 Statement of the Problems

Metal forming is the main problem of the metal industry regarding with the rolling technology for roll pass of structural steel especially in most developing countries. The rolling mill manufacturing industries are contributing few and are not so productive to the maximum possible efficiency; the reason behind this indicates that the ability to understand the properties of metal especially steel type which have different specification with respect to thermo-mechanical properties and also the rolling technology. The technology, remain competitive and efficiently producers must understand the variables that influence operation and properties of the product. One method of achieving the improvement of technology is to analysis the relationship between the variables and parameters that will affect the other parameters will be modeled and analyzed by software to reflect these dependencies. In metal forming, the distribution of temperature and its effect on other physical factors like stress, strain speed in the material is changed due to generation of heat that arises from plastic deformation and transfer of heat to the surrounding air and to the roller. Thus, the temperature effect on stress, strain and speed is important for the simulation of the rolling and high speed forming to describe the temperature evolution of mild steel bloom during the rolling and predict the final mechanical properties of the mild steel during rolling process. The primary object of the rolling process is to reduce the cross sectional area of the work piece and to obtain the desired output likes thermo-mechanical properties and geometrical tolerances. A 3D analysis was done in this study on the steel bloom of square cross section reduced to a thickness required by rolling through the one roll stand with the physical parameters. So to solve above problems finite element model can be applied to simulate stress distribution and deformation of hot metal forming by using mathematical and numerical simulation to determine parameters that have large influence during process using the commercial FE code ABAQUS Software 6.14version.

1.3 Significance of the study

As basic research, it will provide opportunities for the refinement and validation of current process models of hot rolling. The model will facilitate practicing engineers to use advanced technology currently little available in our country and also provide opportunities for professional development in a field where little currently offered. The results of the work will also have future expansion possibilities, including the extension of the capabilities to models to aid in process setup and control in the rolling mill. This work will have a broad impact on the steel industry by providing state-of-practice technology to carry out process and product development that will lead to more competitive products.

1.4 Objectives of the study

1.4.1 General Objective

The general objective of this study would been to analysis a finite element modeling of plastic deformation of mild steel bloom of ASTM A36 and analysis the effect of influential parameters during the process because all metal forming process were parameters and variables dependent.

1.4.2 Specific Objective

- To model two high stand single roll pass hot rolling for the 3D thermo-mechanical deformation using the commercial SOFTWARE ABAQUS version 6.14
- Analysis the main constitutive equations that would been relevant for computer simulation plastic deformation of mild steel.
- Identify parameters that affect the deformation process of bloom of mild steel during hot rolling process using finite element method has been conducted using a computer program called Abaqus/CAE.
- Analysis the principal goal of rolling simulation to connect the process variables speed, rolling temperature, rolling stand geometry, strain, stress field and performed numerical simulations.

1.5 Limitation of the study

Some of the limitation that may be encountered while conducting the research includes: lack of getting all required data for analyzing the thermo mechanical properties of the mild steel.

1.6 Scope of the study

Metal forming has two major functions: the first is the generation of product geometry, and investigate the mechanics of plastic deformation processes with the broad objectives and the generation of mechanical properties. The goal of this work is to develop a finite element analysis model that can be used as a tool in order to analyze the metal forming process of under different parameters which used to understand the behavior as it flows through the single hot rolling mills stand. The basic principles of metal forming process for example flat products will be studied and modeled using non-linear FEM. From the above aspects: materials science, mathematical models of rolling, theory of plasticity and mechanical aspects, heat transfer issues, etc., then focusing on the finite element method by concerning the problem, such as coupled thermo-mechanical analysis, thermo mechanical finite element modeling, and all the non-linear aspects of the problem will be analyzed. The degree of deformation, stresses and strains, strain rates, as well as other parameters of interest, on the work piece and in the rolls will be analyses. The transfer of heat from the work piece to the rolls, heat generation due to the friction heat can be accurately modeled., To achieve this goal developed a mathematical model to predict the distribution of strain, strain rate and temperature using the commercial finite element software package ABAQUS since it has an excellent built in non-linear heat transfer and stress analysis capabilities to predict the effects of each parameters that we used and the empirical relationship between stress, strain and temperature.

1.7 The Motivation this Thesis

Because of the complex deformation hot rolling in metal forming, most of the works are limited to simple geometries such as less thickness and simulation of the process is a cumbersome work in terms of model preparation and computation duration. Moreover, analysis of the effects of hot rolling on the final product is another critical issue. Hot rolling involves preparing physical models of the rolled products, as an aid to analyzing factors such as temperature, stresses, strain, strain rate and rolled product shapes. Although many investigators are working on hot rolling and many methods have been published, some fields remain practically unexplored. Each technique has its own advantage and limitations. The quality and reliability of hot rolling can only be achieved through an understanding of the mechanical factors (rolling speed, strain, and strain rate), geometric factors and physical factors on the rolling process. There is still much work that needs to be carried out on the hot rolling, especially for the materials that have large thickness which need large deformation to get the desired thickness and shape in simple roller arrangement and short time during the operation. A common problem for the existing hot rolling process and method is that each method can only be applied for a specific application case. A methodology which could integrate the thermo-mechanical process and finite element methods would be very useful and powerful for the hot rolling, especially for inexperienced. It is suggested that high quality rolling product can be achieved by comparing existing methods to find the best approach, which gives a best fit for a specific rolling process. The work presented in this thesis aims to integrate the knowledge obtained from the extant literatures into a thermo-mechanical approaches and finite element methods system.

1.8 Thesis Layout/Organization

An appropriate constitutive equation; predicting parameters and modeling the rolling pass schedule. Although no experiments have been carried out, reliable data have been extracted from external PhD theses and the literature supplied by the steel companies that provided by other academic research groups. It should be emphasized that the data provided by the steel companies are especially valuable because they are usually commercially sensitive. This thesis is divided into seven chapters. In the first chapter background, objective, statement of the problem, scope and limitation of the paper are discussed. In chapter two includes a brief review of literatures related to the research have been investigated. In chapter three materials used, dimensions and methodology for deformation at different conditions and the principal formulation and analysis techniques of the thermo-mechanical coupled have been discussed and the equations of equilibrium of the governing equations for both the mechanical and thermal problems are shown, together with their appropriate boundary conditions. At this point it is shown that numerically, the rolling problem consists of a pair of very large and complicated initial boundary value condition mechanical, and thermal. These two mechanical and thermal initial boundary value need to be solved simultaneously due to the strong coupling between the thermal and the mechanical parts of the problem. Fourth chapter FEM concepts needed to develop the models the rolling problem have been explained and the second part of this chapter will explain how the mathematics and mechanics of the problem are implemented into the finite element method. The Rigid-plastic flow, the rigid-plastic flow finite element methods material models will then be analyzed in detail. Finally, the different types of non-linearity's present in the hot rolling process, material, geometric, boundary, and heat transfer, are explained and the creation of the different FEM models that are needed in order to meet the goals of this thesis. All of the features of the models initial conditions, boundary conditions; contact problems, material properties, etc are addressed. The fifth chapter deals with the analysis and the discussion of the results obtained from the simulation FEM and results are presented showing the answers to which we arrived after studying the solutions provided by the FEM. Finally the last chapter is explain the conclusions obtained from this study and the discussion of the future work that needs to be accomplished in order to advance in the research of this challenging and fascinating problem.

CHAPTER 2

Literature Review

2.1 Theoretical Reviews

The purpose of rolling is to convert material of large cross-sections into smaller sections of various shapes. This deformation is accomplished by applying compressive force through a set of rolls. Although hot rolling has been extensively studied by a large number of researchers only few have totally tackled the hot rolling problem. The objective of review the related literature is to summarize the work of different researchers in the field of rolling process using finite element model analysis. Numerous studies have been done to identify the effect of different parameters on the quality of the product. The effects of several parameters such as thickness reduction, rolling speed, initial thickness of work piece and heat transfer coefficient were considered. Thermos-mechanical approach was applied to the hot rolling of steel and the heat transfer phenomenon was considered simultaneously. In this work finite element package ABAQUS software was used, the material taken was ASTM A36 mild steel; the bloom. Generally hot rolling is a metal forming process for the production of metallic profiles with a well defined cross-section geometry consists of a preformed bloom, with square or circular shape, which is the heated metal is passed between a set of cylindrical rolls in order to reduce thickness of the work piece. Most of the steel produced is rolled into strips, sheets, bars and other shapes such as beams or L cross sections. Different end-product shapes require different types of metal forming processes. A few of them are flat rolling, profile rolling, ring rolling, powder rolling, electric resistance rolling, tube rolling etc. Most common metal used nearly in all industrial and domestic purposes is mild steel. Mild steel is relatively economical and possess metal properties that making it suitable for many uses. Depending on the size of input work piece metal forming is classified into two basic categories, namely bulk deformation and sheet metal working processes. Generally bulk deformation processes characterized by the most significant large deformations and the surface area-to-volume me of the work is relatively small. Some of the researches' outputs in relation to the objective of this thesis are: Two major approaches were introduced to investigate the large deformation metal forming problems during the 1970's are first, the "flow" approach, in which assumed the metal as a non-Newtonian fluid having a plastic or rigid-plastic behavior. Compared to large plastic strains the elastic deformation can be ignored and thus solution procedure is simplified. The rigid-plastic material characterization and demonstrated that the rigid-plastic FEM could be applied to metal-forming analysis were developed efficiently in 1973, Kobayashi and Lee (197). Advancements if the process simulations using this method have been made by improving the technique and expanding its capabilities (198-210). The rigid-plastic finite element method generalized by Zienkiewicz et al based on the plastic formulation and capable of analyzing hot rolling, rate dependent processes. Rigid-plastic analysis is taken as the limiting specialization to the isothermal rate-insensitive situations[21,22].

Leardi [22]The main objective of metal forming is manufacture the product with the required dimensional accuracy, surface that free from defects, and with excellent mechanical properties. The parameters for the process are important to meet increasing requirements for desired quality and geometrical properties of rolled materials or work piece. The large number of variables involved and the process characteristics, make the use of finite element tools an effective and attractive opportunity towards understanding of the metal forming process. Because it is powerful and viable method for to predict the effect of applied parameters on the rolling process and it reduce the computational effort. Nonlinear finite element models developed for a large set of complex cross-section shapes and validated against experimental evidences provided by real plant products at each stage of the deformation sequence. Depending on the validated value finite element models, is applied to investigate the effect of many parameters on the flat rolling process. As is well known the effects of main variables on material, flow behavior and geometrical features of a rolled metal or work piece analyzed. The parameters that selected as factors are rolling temperature, diameter and draught (diameter reduction), and angular velocity. In the case of metal forming operations, under the hot and cold rolling elastic strains contribution is negligible with respect to nonlinear plastic strains, a rigid-plastic approach can be reasonably adopted for the analysis. As it is well known there is a complex interconnection between thermal and mechanical problems why they to be solved simultaneously. The thermo-mechanical coupling occurs when large plastic deformations and contact pressure generate heat transfer which is a source of changes in the mechanical problem. Formulation of Updated Lagrangian through the software is selected to solve the coupled thermo-mechanical problem.

Komori [23] Analyze the finite-element method, which coincides with the finite-element mesh of deformation. However, heat conduction occurs between the material (high-temperature) and the roll (room-temperature), the flow of temperature at the material-roll contact surface towards the low temperature and shows it by simulation when the hot rolling process is performed. As pointed out by the authors analyzing deformation is the conventional 3D rigid-plastic finite element method. As is well known the finite element method is utilized mainly, which requires a large amount of computation time and memory capacity. In this case the finite-element mesh effect in the cross section of the material is investigated due to the finite-element mesh derived from the mesh rolling is analyzed. Due to the turn of the material in the region between two rolling mills, not the one-fourth of the material the whole material is analyzed. In the numerical simulation of the finite-element mesh in the cross section of the material influences calculated results. The shape of the material obtained by the analysis agrees well with the shape of the product. Hence, the validity of the simulation is demonstrated.

X. Wang1 [34] hot rolling processes a numerical simulation dependent on the accuracy and reliability of a suitable material modeling, which plays the important and foremost role in the analysis and metal flow behavior. In the present study, high temperatures up to 1300℃ used carried out hot compression tests and varying strain rates for medium carbon micro-alloyed steel. Johnson-Cook model (JC) and a Zerilli-Armstrong (ZA) model were developed and exhibited limitation in characterizing complex plastic behavior based on experimental results. Investigation of strain hardening and the coupled effect of temperature and strain rate was introduced and calibrated through a combined JC and ZA model. Better agreement with experimental data results showed that the combined JC and ZA model demonstrated. The proposed material model was coded and implemented into a finite element model simulating the industrial hot rolling and simulated rolling torque was in good agreement with experimental data. Nonlinear mass flow behavior of the steel bar investigates from the plastic strain and stress distributions were recorded. Results showed that the maximum equivalent plastic strain occurred at 45^0 and135^0 areas of the cross section. With decreasing temperature Stress increased, and the corresponding rolling torque was also increased. Rolling speed had limited influence on the internal stress of the bar due to the extent of plastic deformation, but the relative rolling torque was increased due to strain rate hardening.

Alejandro Rivera Muniz [19] In what follows deformation processes are the processes by which we obtain of the required shape of the production through applying of plastic deformation process on the metal, by using different mechanism of forming called hot forming and the others by no using the temperature which called cold forming. As a result thermal-mechanical coupled approach is used to account for the phenomena resulting from the pressure-dependent contact resistance between the work piece and the tools called roller and stress and strain variations occur due to rolling force/pressure imparted by roll contact, and non-uniform temperature distribution. The hot and cold rolling processes have been developed for flat rolling work piece with rectangular cross section using finite element method. Finite element methods provide an effective and economic way to model these thermo-mechanical processes and the associated mass flow behavior. The flat rolling of hot and cold steel rectangular strips under a series of different parameters, providing the rolling designer with a tool that he can use to understand the behavior of the steel as it flows through the different passes and model can be used to analyze easily. The non-linearity present in the rolling problem: material, geometric, boundary, and heat transfer are developed. As pointed out by the authors the modeling can be predicts the equivalent stress, equivalent plastic strain, maximum strain rate, equivalent total strain, temperature of the work piece , roll temperature, work piece length, slab thickness % reduction (draft), and velocity, for both the cold and hot rolling processes. The quality of final product is highly dependent on the thermo-mechanical deformation and mass flow behavior during hot rolling. The finite element model results are an improvement over the results obtained through the classical theory of rolling. The work also demonstrates the role that contact, heat generation due to friction and heat generated during the rolling process.

D. Demin[25] Most of the time, metal forming process especially rolling process will be discussed in terms of hot and cold rolling process. A rolling process of AISI-304 bar was studied by laboratory experiments and numerical modeling in order to evaluate the effect of boundary conditions and simulation techniques on the model predictions. At the same time both models behave similar with the variation of boundary conditions: broadening is larger if the temperature gradient is taken into consideration, the relative increasing of the effective strain in the specimen center with the increasing of reduction is very similar. The simulations of metal forming process were performed by two different techniques based on finite element method.

The first technique solves three dimensional problems. This technique is based on assumption that flat cross section of a billet remains flat during the rolling process. Thus 3D distribution of deformation characteristics is constructed as a set of solutions in flat sections. The second one is sequential solution of a series of generalized plane problems. Each technique was used for solving of isothermal forming task and non-isothermal one. The results were compared with laboratory rolling performed with different reductions and at different temperatures. It was found that the difference of initial temperature is inconsequential to the prediction of strain and strain-rate distributions. This observation was confirmed experimentally.

A. Romagos [26]As is well known, metal forming under the hot rolling is an important deformation process in steel manufacturing which a slab is studied by using the rigid-plastic finite element method. Modeling of the roll and the slab are developed to investigate the effect of initial rolling temperature, slab thickness, rolling speed, friction coefficient, and reduction rate on the rolling force, normal force, and effective stress distribution. The shape forming process for example rolling involves in the types of material, geometry and contact nonlinearities, and it is difficult to obtain analytical solution. Rolling method and physical experiment method have thus been often used to study rolling properties over the past decades at the expense of time and cost. Due to the result of technology numerical simulation technology solves rolling problems and can shorten development periods, and reduce the cost of research and development. From numerical simulation the prediction of rolling pressure and rolling force of wire, calculation of rolling pressure of strip simulation of stress and temperature study of deformation of strip and discussion of strain and stress. Finite element method and numerical simulations have been proved to be a very powerful tool used to indicate the effect of different parameters that applied during the hot rolling like rolling force and other.

Kuziak,Yi-Wen Cheng,Miroslaw Roman Glowacki,Maciej Pietrzyk [27] In this research paper modeling of the micro structural evolution of steels during thermo mechanical processing has increased our understanding of the austenite micro structural restoration processes occurring during and after plastic deformation. Modeling can accurately characterize the sequences and interactions of the mechanisms that change the microstructure. Thus, we can predict the effects of chemical composition and processing parameters on the final microstructure and mechanical properties of steel. Modeling is an efficient tool for the development of new steel grades and for optimizing production technologies, it has great potential for improving the manufacturing processes and reducing the cost of steel products. The ultimate goal of modeling industrial processes is to predict the mechanical properties of commercial products. They relate processing parameters, such as strain, strain rate, and temperature, to microstructures features, such as volume fraction of the recrystallized material and austenite grain size, with emphasis on the effect of micro structural changes on the mechanical properties of the final product. Model predicted mechanical properties were compared with values measured in laboratory and industrial experiments. The models gave an accurate, quantitative characterization of the plates, rods, and rails subjected to rolling processes. It is possible that the results of this study provide a basis for future optimization of the chemical composition and processing of steels.

F. Micari [3] By far the most common metal forming process hot rolling is generally analyzed by means of some simplifying hypotheses: most of the developed theories assume that the operation is conducted by coupled thermo-mechanical analysis and that plane strain conditions occur. In this paper a 3D coupled thermal-mechanical analysis is carried out concerning some hot plate rolling processes in order to investigate the process mechanics. The geometrical parameters of the work pieces and of the rolls and the operating conditions have been selected in order to compare the numerical results with some available experimental data.

Limei Jing [28] a thorough understanding of the available roll design methods; and a condition of their application is extremely important in order to achieve the objective of producing high quality rolled products by reviewed some previously published and experimental and theoretical studies of hot rolling. Successful hot roll is dominated by the calculations of some important parameters, which describe two-dimensional or three-dimensional deformation in the work piece. These parameters, such as roll separation force, torque, elongation, spread and draft, are discussed in detail. The method or formula for the calculation of each parameter is different for each set of different application conditions. A thorough study of these methods in different application cases will lead to the hot rolled products .Finite element is an important method which has been employed in the study of hot rolling. The theory, of commercial software and application cases has been described. 2D and 3D finite element methods for hot rolling simulation have also been discussed within the work. The current techniques and the problems of using the Finite Element system in hot roll design have been presented briefly. Possible solutions to these problems have also been discussed and there need to be considered in order to successfully apply Finite Element theory in hot roll design. An important alternative approach for hot roll design has been introduced in this thesis. A Matrix -based roll design system has been developed. It includes a Matrix -based system for flat and section roll designs. The realization of the Matrix-based system is discussed. All the methods and formulae considered previously can be integrated in the proposed roll design system. The approach emphasizes the need for teamwork. The design procedure allows both less experienced designers and senior designers to benefit from participation. It is suggested that high quality rolled products could be achieved from optimized designs produced using this systematized the approach compared to the ad-hoc use of existing techniques, formulae and methods.

Vitalii Skliar, [29]The implementation of mathematical modeling study of a new two-stage soft reduction method of continuously cast blooms rolled in cross rolls are presented in a current work. As a result the initial stage of investigations of the mathematical model based on FEM method has been designed. In this case, we assumed that the conducted calculation mechanism influence on the stress strain state depends on deformation parameters and shape of a work tool has been investigated. Mathematical model adequacy with help of physical modeling has shown high reproducibility of results verification. The optimal parameters of deformation process, which provide the minimal stress level in metal, have been determined. It has been found, that effectiveness of deformation penetration into axial zone of continuously cast bloom using a new method is no less than 15 % higher than in case of one-stage deformation scheme.

J.G Lenard, M.Pietrzyk, L.Cser [21] has in this paper the mathematical and physical modeling of flat rolling process described. Here he gives us a detailed account of Flat rolling process .Plasticity of material during rolling and compression, roll deformation, roll separating force, roll pressure, shear stress, and friction, Friction factor and coefficient of friction.Schey's model, sim's model, Orowan model and refinements to Orowan model, Temperature gain and loss during rolling .Static, dynamic and Meta dynamic recrystallization, Roll torque and power calculations, Influence of physical quantities on rolling, and flexible rolling, Comparison of some calculations, Base of computational simulation to be done.

Jianhua Ren, Wei Wang, Rong Liu [30] In order to accurately reflect the whole rolled-piece deformation, the ingressive material size is the primitive billet size is necessary to simulates the deformations of processes. The calculated results from ingressive material shapes and sizes of processes through every process can also be recorded as the ingressive one of the next process. The models are re-established and the grids are divided again according to the shape of the incoming material before the next process simulation. Through above method, deformation in whole process can be reflected entirely. 3D finite element analysis program is used as work platform, the high-speed wire rod rolling process of φ20 bar as the research object to be simulated numerically, using the method of 'simulation analysis optimization 'to research .The first step work of the 12 rolling process is as an example to show the simulating process and results. The stress field, strain field are simulated in the process of high speed wire rod rolling .Through analysis, the defects of rolling technology were found out. Therefore, the optimum design is gotten and then simulated which improved the actual production process and avoided the original defects. So the optimum design is proved feasible in groove design and the optimization of process parameters in the production process. The paper is trying to find out the law of three-dimension metal flow in the rolling process of high-speed rod and summarize the regularity of the metal deformation. Some viewpoints are proposed about the correct pass design and the technical parameter of optimization in producing process.

Kuziak,Yi-Wen Cheng,Miroslaw Roman Glowacki,Maciej Pietrzyk [27] In this research paper modeling of the micro structural evolution of steels during thermo mechanical processing has increased our understanding of the austenite micro structural restoration processes occurring during and after plastic deformation. Modeling can accurately characterize the sequences and interactions of the mechanisms that change the microstructure. Thus, we can predict the effects of chemical composition and processing parameters on the final microstructure and mechanical properties of steel. Modeling is an efficient tool for the development of new steel grades and for optimizing production technologies, it has great potential for improving the manufacturing processes and reducing the cost of steel products. The ultimate goal of modeling industrial processes is to predict the mechanical properties of commercial products. They relate processing parameters, such as strain, strain rate, and temperature, to microstructures features, such as volume fraction of the recrystallized material and austenite grain size, with emphasis on the effect of micro structural changes on the mechanical properties of the final product. Model predicted mechanical properties were compared with values measured in laboratory and industrial experiments. The models gave an accurate, quantitative characterization of the plates, rods, and rails subjected to rolling processes. It is possible that the results of this study provide a basis for future optimization of the chemical composition and processing of steels.

V. N. DANCHENKO [31] It is interesting to note that plastic deformation of ferrous metals, non-ferrous metals and alloys presents in this paper. The deformation is conducted in heated state for decreasing the strain resistance and increasing the plasticity of the worked metal. The rise in temperature no higher than (0.3-0.4)Tf (Tf – the metal fusion temperature in absolute scale, ºK) doesn't bring the structure changes to the metal, but the acceleration of diffusion processes contributes to the healing of structure defects and drop of inner stresses in metal. At temperatures of heating higher than 0.4Tf the process of grain recovery takes place in the metal. The processes of structure deformation and metal hardening connected with deformation are going on simultaneously during the process of hot metal forming as well as the process of formation of new structure as the result of grain recovery following by the weakening.

A. Romagos [26]As is well known, metal forming under the hot rolling is an important deformation process in steel manufacturing which a slab is studied by using the rigid-plastic finite element method. Modeling of the roll and the slab are developed to investigate the effect of initial rolling temperature, slab thickness, rolling speed, friction coefficient, and reduction rate on the rolling force, normal force, and effective stress distribution. The shape forming process for example rolling involves in the types of material, geometry and contact nonlinearities, and it is difficult to obtain analytical solution. Rolling method and physical experiment method have thus been often used to study rolling properties over the past decades at the expense of time and cost. Due to the result of technology numerical simulation technology solves rolling problems and can shorten development periods, and reduce the cost of research and development. From numerical simulation the prediction of rolling pressure and rolling force of wire, calculation of rolling pressure of strip simulation of stress and temperature study of deformation of strip and discussion of strain and stress. Finite element method and numerical simulations have been proved to be a very powerful tool used to indicate the effect of different parameters that applied during the hot rolling like rolling force and other. Moreover, friction distribution in the deformation zone is also studied based on 3D models.

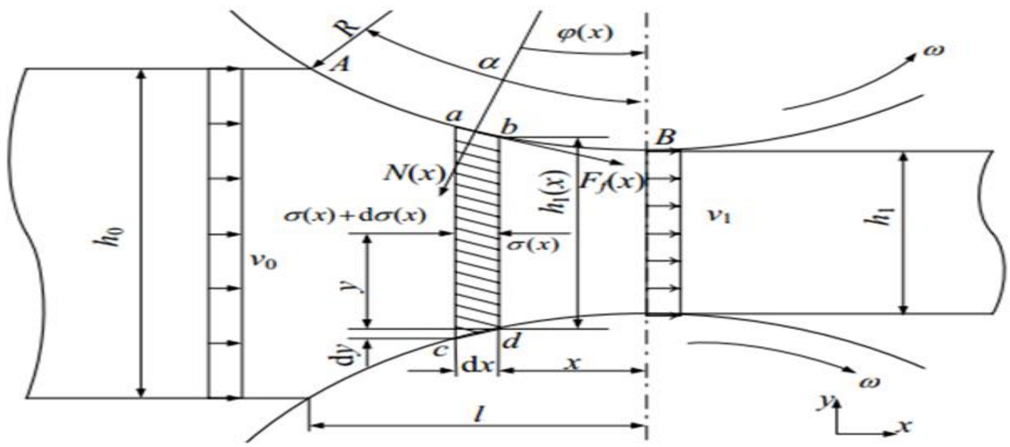


Figure2. 1: Geometry of slab rolling process

The slab (abcd) or microelement bodies in the deformation zone was usually employed to analysis or develop the modeling of rolling force, as shown in Fig. 1above.In this case the basic assumptions and equilibrium conditions, the analytical equation of unit force (Karman equation) is obtained based on any microelement body (abcd) in the deformation zone.

$$\frac{dN(x)}{dx} - \frac{K}{y}\frac{dy}{dx} \pm \frac{F_f(x)}{y} = 0 \qquad 2.1$$

Where N(x) is unit force, K is metal natural intensity and $F_f(x)$ is unit friction. It is assumed that contact condition in the deformation zone obeys Coulomb friction model. If the chord is used to represent the contact arc, the distribution of unit pressure can be expressed as

$$N(x) = \frac{K}{\delta}\left[(\delta \mp 1)\left(\frac{h_0}{h_1(x)}\right)^{\delta} \pm 1\right] \qquad 2.2$$

Where $\delta = \frac{2lf}{\Delta h}$, Δh is reduction rate, h_0 is initial work-piece height, and $h_1(x)$ is the height after rolling. It is found that the main factors affecting unit pressure are friction coefficient, roller diameters, reduction rate, work piece height and tensile force. some simplifying assumptions are employed in the hot rolling technology process parameters rolling and its parameters, rolling force and their relationship parameters, force rolling, pressure during rolling, roll bite condition, angle of contact, the reduction, analysis of rolling load, friction and its effect and friction in rolling.

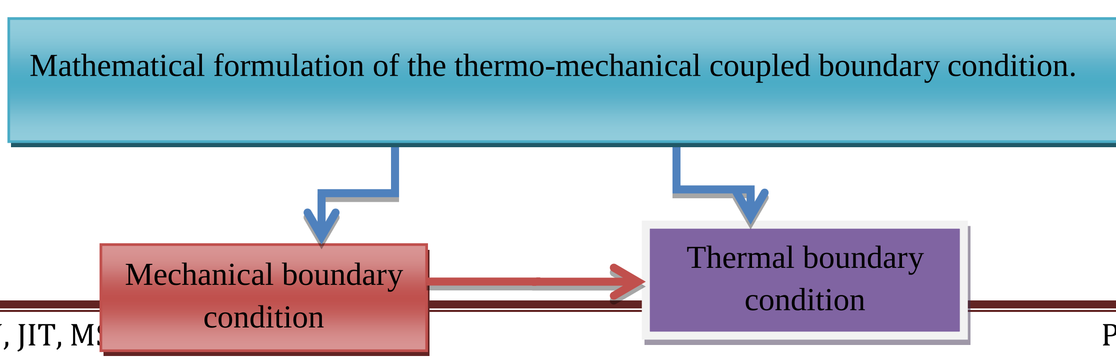
2.1.4 Gap of Research Work

In different literature the thermo-mechanical output properties of the hot rolling process focuses on the effects, roll diameter size, angle of bite and pressure exerted by roller on the work piece but less attention given on the stress-strain curve relationship which have great power to determine the thermo-mechanical properties of the bloom mild steel. So the relationship of stress-strain with different value of temperature gets more attention in this paper to know the properties of the rolled metal and as well as geometric properties of rolled products and understands the issue of hot rolling in itself very complex because hot rolling is a process that depends significantly on the flow stress of metal at high temperature, plastic deformation and physicochemical processes. In general the aim of this paper is to know the effects of each parameter during the rolling process or deformation in the rolling process, because under hot rolling process the metal is subjected to a complex flow stress, stress and strain.

CHAPTER THREE

Materials and Research Methodology

This paper took the high temperature rolling process of bloom as the research object and to be simulated numerically under the thermo-mechanical process with the finite element software ABAQUS. The simulation results were compared with the actual operation of the production process, the rolling simulation reappeared the actual production situation, realized the visualization of the rolling process. In the field of metal forming simulation, with the increasing of people's needs, there were a lot more mature commercial simulation software's which are convenient for researchers using numerical simulation technique to study the industrial process. ABAQUS/CAE is a finite element process simulation system to be applied for the analysis of metal forming and various forming process in related industries and heat treatment process rolling system is the preparation of a series of roll pockets sequences for roll passes that are necessary to obtain a desired shape and desired thickness of the rolled material. The fast improvements in computer software technologies have boosted commercial finite element analysis packages to analyze complex structures. One of the most popular brand and power full packages is ABAQUS. In order to meet the objectives of this research, nonlinear finite element analysis on the bloom mild steel subjected to hot rolling plastic deformation was modeled using ABAQUS 6.14 to investigate the effects different parameters that involved during the operation process and cyclic deterioration and resistance mechanisms in terms, deformation. In this research, the overall response subjected to different load and factors affecting the hot rolling are identified. This chapter deals with the overall process and method of modeling, analysis and results of nonlinear finite element analysis using ABAQUS/Standard 6.14 software.



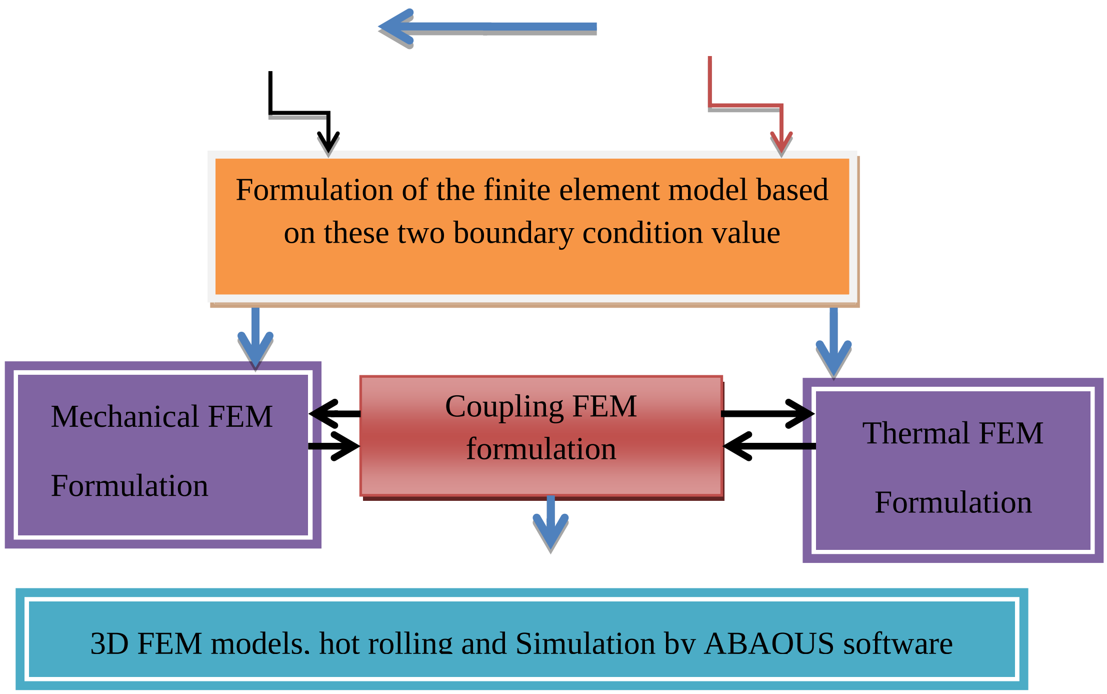


Figure3. 1: Research methodology flow chart.

3.1 Deformation in rolling zone

Deformation in metal forming is defined as physical phenomenon occurred in metal through the forming process, to give some results in changing of the shape and the volume, which may be able to see and measure by some ways as a function to the strain in the metal which represents the positive and negative elongation when applying tensile or compressive load and The strain may be divided to two parts (elastic strain: is the strain in which the metal returns to its original shape after the removal of the load, and proportion with applied stress) and (plastic strain: is the strain which remains in the metal after the removal of the load, having the stability state, occur in the metal due to the applied stress over the elastic limit)[1].The longitudinal rolling is a continuous forming process, in the course of which the rotating rolls pull the rolled stock into the roll gap and press it within. These events are not going on at the given moment in the whole volume of the formed material, but only in its limited part in deformation zone. The deformation zone is defined by contact arc length (the projected roll gap length) and mean width. Geometrical characteristic of rolling zone is shown in Figure 4.Total relative deformation ε obtained for one pass of material through rolling mill is given [32].

$$\varepsilon = \frac{(h_o - h_1)}{h_o} \quad (3.2)$$

Where h_0 thickness of work is piece at the input into rollers and $h_1$is thickness of material at the output from rollers. However, the equation (3.3) does not describe distribution of deformation in the rolling zone. Point E in rolling zone (see Figure 3.2) is characterized by distance x from origin of coordinates and thickness h_x. Then, relative deformation ε of rolled material after pass point B to point E is given by formula:

$$\varepsilon_x = \frac{(h_o - h_x)}{h_o} \quad (3.3)$$

Where thickness h_x is established by equation of a circle with diameter 2R and displacement y in Y direction within the distance Y_0.

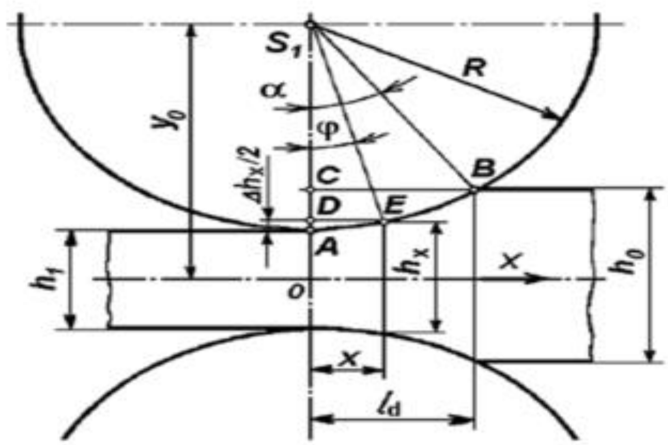


Figure3. 2: Geometry of rolling zone.

$$x^2 + (\mathrm{y} - y_o) = R^2 \quad (3.4)$$

Thickness h_x is equal to double of y coordinate in point E

$$h_x = 2\left(y_o - \sqrt{R^2 - X^2}\right) \quad (3.5)$$

Displacement of circle center y_o is equal to the sum of roller radius R and half thickness of material at the output ${h_1}/{2}$.

$$y_o = R + \frac{h_1}{2} \quad (3.6)$$

Substituting the equations (3.32) and (3.33) into the equation (3.34) gives the relation.

$$\varepsilon_x = \frac{h_0 - h_1 - 2R + \sqrt{R^2 - x^2}}{h_0} \tag{3.7}$$

It can be seen that total relative deformation ε (see equation (3.32) is involved in the equation (3.36).By introducing the substitution ε into the equation (3.36) and after retreatment we obtain the equation which describes distribution of relative deformation in rolling zone along the length of Contact arc L_d

$$\varepsilon_x = \varepsilon - 2.\frac{R}{h_o}.\left[1 - \sqrt{1 - \left(\frac{x}{R}\right)^2}\right] \tag{3.8}$$

Coordinate x belongs to the interval [0, l_d]. The length of contact arc l_d can be obtained from formula

$$l_d = \sqrt{(R.\Delta h - {}^{\Delta h^2}/_4)} \tag{3.9}$$

$$l_d = \sqrt{R.\Delta h} \tag{3.10}$$

3.2 Rolling & its Parameters

When a piece of metal is rolled between two rolls, the work piece experiences both vertical and horizontal stresses caused by the compressive load from the rolls and the restrains by the portions of the work piece before and after the material in contact with the roll respectively. As the rolls exert a vertical stress on the work piece, the latter exerts the same amount of stress back onto the rolls itself. As such the rolls are subjected to elastic deformation due to this stress induced by the work piece [33].Elongation, spread and draft are important parameters which describe the 3D deformation of a work piece in hot rolling. The early work theory of rolling has focused on two-dimensional deformation, where the ratio of the width to thickness of the work piece is high and the spread of the work piece is considered negligible. Nowadays it has been more important to study and predict metal flow in all directions in order to accurately control the material properties and final quality of the rolled products. Figure 3.3 shows a flat rolling process for the deformation of the parallelepiped of material shown in the figure and, draft is expressed as a linear reduction in height of the work piece under the action of the compressive force.

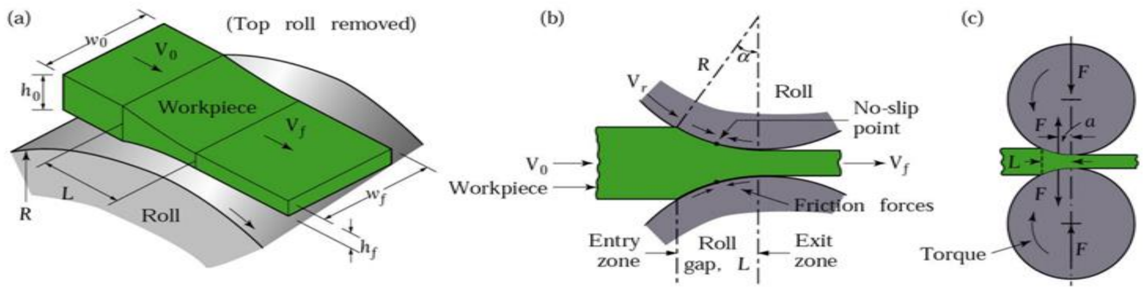


Figure3. 3 :Flat rolling process analysis.

Elongation is defined as the increase in length of the rolled material. Elongation is expressed by different methods. The lateral flow of the metal in the roll gap causes enlargement (exceptionally even reduction) of the rolled stock width and is called spread .In the rolling process, any compression applied to the metal causes it to elongate in the direction of rolling and to spread in the transverse direction, as we see from the figure 3.3 above. Spread is an increase in width of the rolled material that is being reduced in thickness. Spread is often expressed as a difference between maximum values of widths before and after rolling.

3.3 Microstructure Evolution during Hot Deformation

In the modern hot forming practice, achieving the desired mechanical properties of the product is of prime importance to engineering. The description of deformation resistance behavior of steel and its microstructure development under hot rolling conditions is still the most commonly used and the most powerful. The phase transformations during the process of steels allow large versatility of microstructures, and the different possibilities concerning microconstituents and mechanical properties can be transformed in new products. The microstructural evolution during hot deformation of microalloyed steels involves accumulation, annihilation and rearrangement of dislocations, recrystallization and grain growth. For hot deformation, the microstructural evolution that occurs in the material is dependent on the size of the reductions, the strain rate, the temperature and the length of the holding times between reductions. For hot bloom rolling of steel it is the desired final mechanical and geometrical properties of the bloom that determines the so called rolling schedule, which is the setup for the rolling process, i.e. the amount of reduction, the rolling velocity and the temperature. The stored energy due to the accumulated dislocations during deformation is generally lowered by three processes: recovery, recrystallization and grain growth. Recovery is a process where annihilation and rearrangement of the dislocations occurs. Recrystallization involves the formation of new dislocation free grains. The grains grow on the expense of the old deformed grains, leaving a new structure with low dislocation density. Grain growth is the process when the grains coarsen and the grain boundary area is reduced. Recovery and recrystallization can take place during and after deformation and to distinguish them they are called dynamic and static, respectively. If the recrystallization after deformation is preceded by dynamic recrystallization it is called metadynamic. Metadynamic recrystallization is the continuation of the dynamic recrystallization at the end of deformation and the nuclei for recrystallization are thus already present[21].

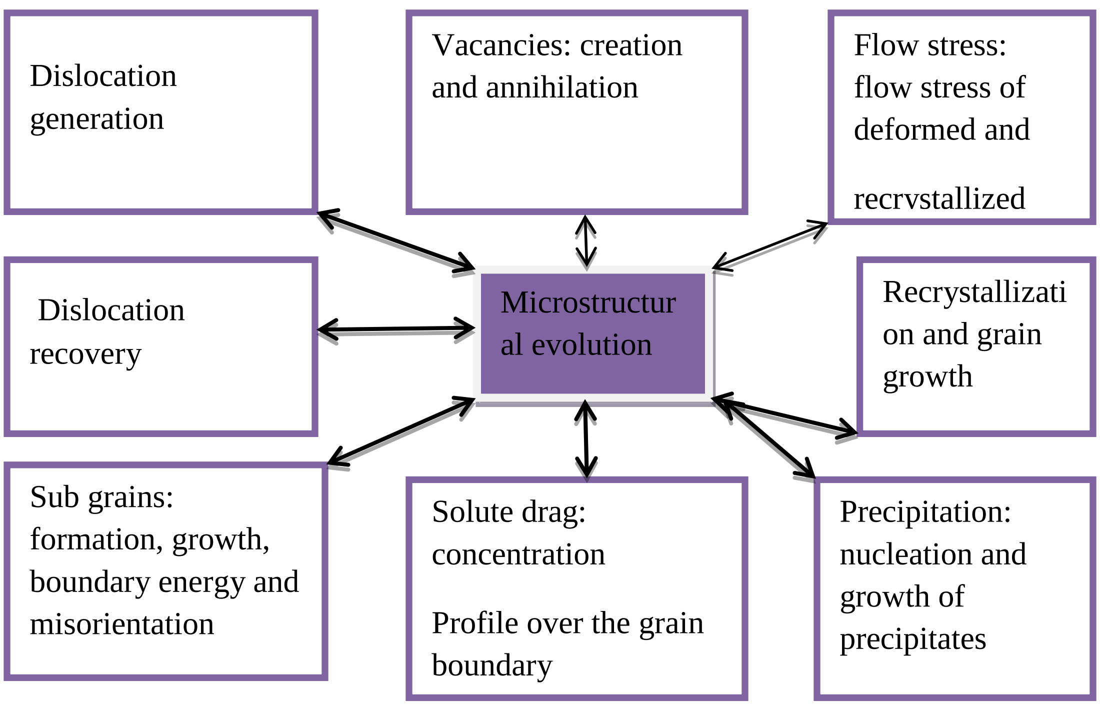
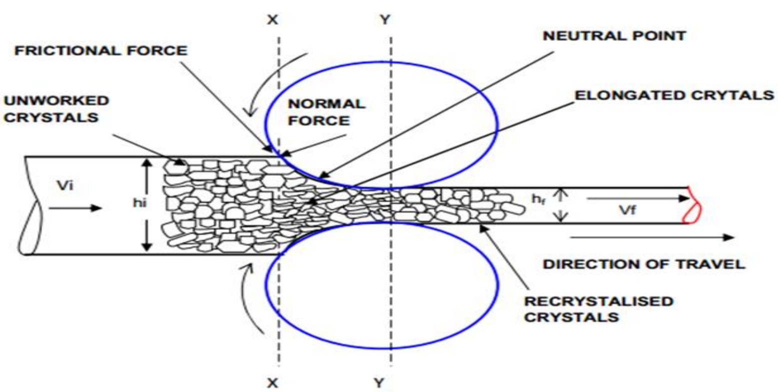


Figure3. 4: Outline of the sub-models that together represents the microstructural model.

Generally the microstructure is a product of parameters like strain, strain rate and temperature due to a number of microstructural mechanisms. These mechanisms can both harden and soften the material. In other words, the ability to slip is made harder or easier. During hot deformation, mainly three different mechanisms must be taken into consideration: work hardening, recovery and recrystallization[18].

3.4 Recrystallization in the Deformation Processes

The definition of recrystallization is “the formation of a new grain structure in a deformed material by the formation and migration of high angle grain boundaries driven by the stored energy of deformation. An interesting feature of the rolling process was the possibility of initiating dynamic recrystallization in the central part of the deformed material**.** The distinction between hot and cold rolling depends on the processing temperature with respect to the recrystallization temperature of material. Rolling is classified according to the temperature of the metal rolled. If the temperature of the metal stock is above its recrystallization temperature then the process is termed as hot rolling, whereas if the temperature of stock is below its recrystallization temperature the process is known as cold rolling. Hot rolling is conducted by raising the temperature of the steel metal stock to its upper critical temperature to its austenitic phase, i.e., above the recrystallisation temperature. Then controlled load is applied which forms the material to the desired profile and specification. While the material is rolled, its temperature is monitored to make sure it remains above the recrystallization temperature. To maintain a safety factor, the finishing temperature is usually 500C to 100° C above the recrystallization temperature. If the temperature does drop below this critical level, then it is not termed as hot rolling. The austenite grains get deformed / elongated in the rolling direction. However, these elongated grains start recrystallising as soon as these come out from the deformation zone.



XX- ENTRY PLANE YY-EXIT PLANE

Figure3. 5 : Hot Rolling & Recrystallisation

The unidirectional austenite grains dissolve as soon as the temperature drops below the upper critical temperature. These are entirely replaced by a new set of grains, to nucleate / recrystallize and grow into ferrite-perlite structure. The recrystallized ferrite-perlite grains maintain equiaxed microstructure and prevent the metal property from becoming unidirectional and work hardened. It is usually accompanied by a reduction in the strength and hardness of a material and a simultaneous increase in the ductility. Recrystallization may occur during or after deformation (during cooling or subsequent heat treatment).The rate of recrystallization is heavily influenced by the amount of deformation applied. Heavily deformed materials recrystallize more rapidly than those deformed to a lesser extent. Indeed, below a certain percentage deformation recrystallization may never occur. Deformation at higher temperatures allows concurrent recovery. Materials recrystallize more slowly than those deformed at room temperature e.g. contrast hot and cold rolling The volume fraction of recrystallized grains increases with temperature for a given time. The most important industrial uses are the softening of metals previously hardened by cold work, which have lost their ductility, and the control of the grain structure in the final product[33].

3.5 Modeling Bloom size (Deformable)

For typical contact analysis, the square bloom is defined as elastic-plastic deformable body and its geometrical shape is described in a discrete form. The material of bloom is high quality of mild steel of ASTM A36 steel and can endure high temperature .A mild steel of ASTM A36 with dimensions 320x320x3000 mm (wxhxl) was used as a the bloom material in this simulation, see figure 7. The gap between the two rolls was less than the thickness the work piece , the rolling operation achieved in one pass under temperature of 1100-1300 ºC. A bloom is piece of raw steel, before it is shaped into a finished product. A bloom is metal that has a square cross-section which is created directly via continuous casting or indirectly via hot rolling an ingot have highly malleable and ductile, which allows them to be hot worked to give *them the specific shapes and properties desired.*

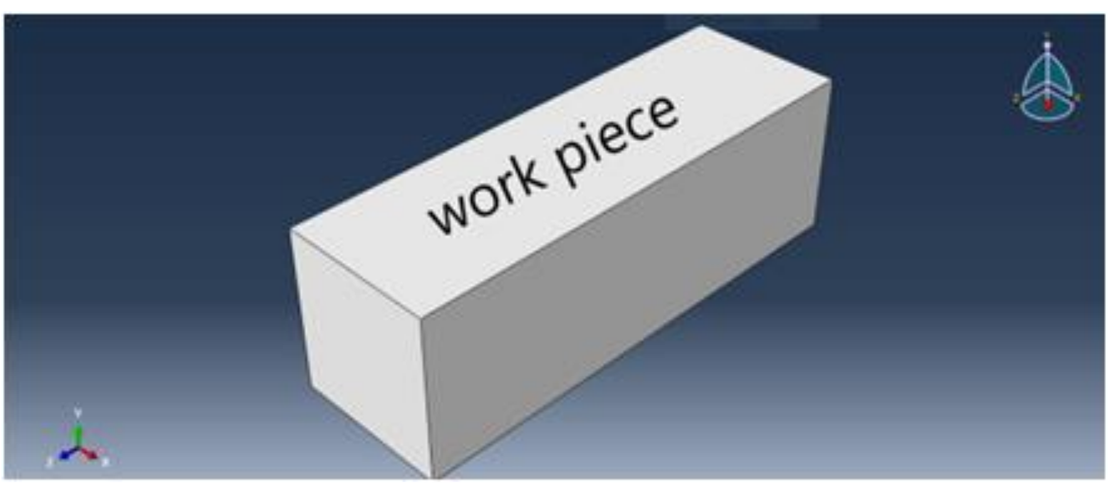


Figure3. 6 :Modeling of bloom by abaqus software.

The material chosen for the specimen is A36 structural steel is chosen because it is commonly used as standard construction material. Appendix D shows the Material properties of A36 structural steel.

3.6 Modeling Roller Size (absolutely Rigid)

The rotating rollers are modeled as rigid contact-bodies. In hot rolling process the main tool is roll and for rolling the desired properties of the roll are playing important role. Rolls are most vital part of a rolling mill. The deformation of metal work piece is directly accomplished by the rolls. The rolling stresses are first of all applied on rolls and after that transmitted to other sections of a mill. Consequently, the rolls had to be harder and more resistive to deformation than the metal under processing [34]. Hardness, stiffness, load, rigidity should be in such a way that the roll should work safely and without unexpected breakage and deformations. It is necessary to know the load applied to the component and to understand the material properties [35]. The roller is a basic part of the roll stand usually modeled in a system as a pair, and considered (assumed) to be rigid or as non-deformable rigid bodies obviously, which only elastic deformation are expected in the roller at least in macroscopic scale and Friction between stock and rolls was modeled using the Coulomb friction law with a friction coefficient, μ and the metal between the rolls is plastically deformed.

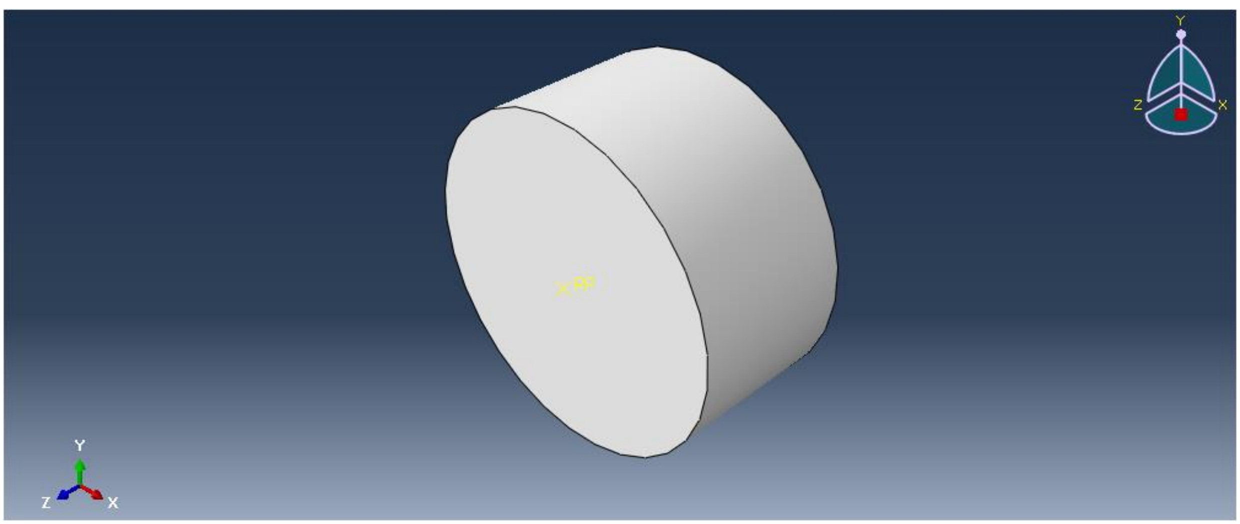


Figure3. 7: Modeling of Roll Geometry

They ensure the required shape, dimension and surface quality of the rolled metal. They transfer the force and torque load to the work piece. They are divided into: as per material and process technology cast iron, steel cast, steel forged, compound, and as per forming technology for rolling of flat products grooved and special, and also as per placing in the roll stand - horizontal and vertical. For work roll generally EN 31Tool Steel is used for rolling of mild steel metal [35]. Rolls are required to carry out the heavy work of reduction necessary for hot rolling. Rolls are tools which have to take all kinds of stresses, loads from normal and abnormal rolling and changing with roll wear during rolling process. Rolls are regularly redressed to rebuild the desired shape and to eliminate the worn, fire-cracked and fatigued surface, and they never last as long as roll users would like. The final goal is always to increase the quality of finished rolled products (tolerances, surface) and at the same time to increase the length of rolling process, to improve roll performance and to reduce the risks of roll damage. Rolls come in a wide variety of sizes; the smallest roll weighs only a few kilograms, the heaviest around 4.5 tons a piece, and the variety of grades used is also wide, from ductile iron to tungsten carbide, cast iron, steel cast, steel forged, compound, covering all kinds of tool steels and special steels, used only for rolls [36]. This study is concerned mainly with steel rolling mill of first pass of roughing bloom deformation using two-high-roughing mill stand which is suitable for hot rolling of the bloom with initial cross-section 192000 mm square and 3 m initial length in one passes. The mass of one bloom was 4500 kg. The rolling material was reinforcement steel mark according to American standard ASTM A36**.** The total length of the roll barrel was 2300mm - 2800 mm, the roll barrel length was 1500 mm and the roll barrel diameter was 950 mm**.** The roll machining due to wearing was estimated after 4500 rolling tons of steel. To reduce the computational time, only one half of the geometric model is considered in numerical simulation due to rolling symmetry. The meshes are very dense in the contact zone, as shown in Figure 10. Thermo-mechanical coupling FEM and isoparametric technology are used to develop the models. The rolls are assumed or considered to be rigid and heat transfer body, and their material is an iron steel of high chromium and the chemical composition is given as: 1.5% C, 0.75% Si, 0.67% Mn, 5.5% Cr, 2.6% Mo, 1.43% V and 1.82% W. The work piece material is a typical carbon steel and its chemical composition is defined as follows: 0.14% C, 0.62% Mn, 0.27% Si, 0.032% P and 0.041% S. It obeys Von Mises yield criterion and the flow rule.

Uniform temperature distribution is assumed throughout the original work piece. The density of the material is 7800/7850 kg/m3and the Poisson's ratio is 0.3. The material's elastic module, heat expansion factor, heat conduction rate and specific heat are the function of temperature.

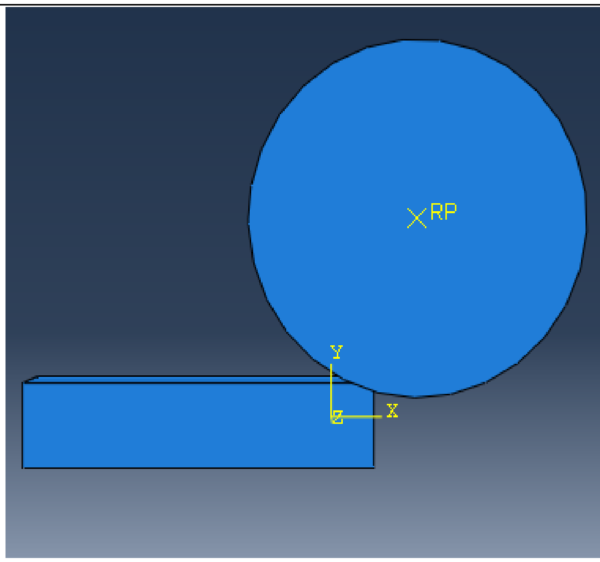
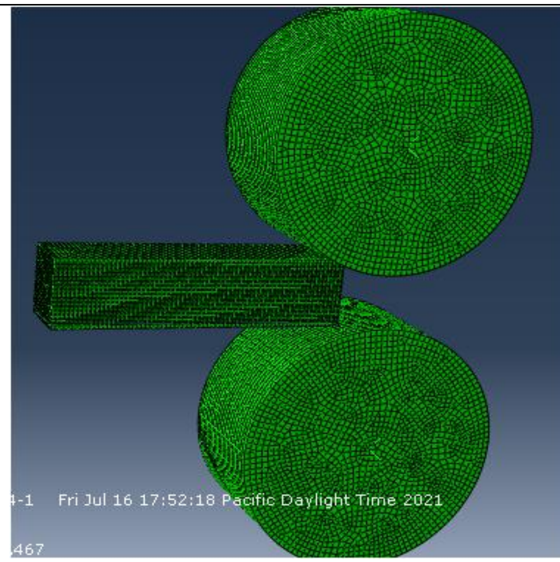
Actual Half-Simulation	Mirrored Results
	

Figure3. 8: The two-high finite element meshes of the square flat blooms and the roll.

The steel bar was built as a three-dimensional deformable part using 8-node brick element (C3D8RT), and rollers were modeled as rigid parts using 4-node rigid element (R3D4)[37]

A 3Dhexaedral element was employed to mesh the complicated geometry of the bloom (especially when deformated). A mesh refinement analysis was performed for the first pass and the analysis showed that a 30-40 mm mesh element size was adequate. The model is able to regenerate the mesh to replace the excessively distorted elements during the simulation of the rolling process. The rolls were considered as rigid bodies for the simulations. In the present work, the rolling mill configuration and the bloom were modeled using ABAQUS software and then exported to the FEM ABAQUS software version 6.14.

Pass sequence number	1(one)
Pass geometry	Square bar (bloom)
Entry cross section dimensions	320x320x3000 (mm)
Rotational speed	300m/s
Roll gap	Less than the thickness of the work piece
Roller dia	800-950(mm)
Angular velocity	7rad/s

Table3. 1: Rolling dimensions and conditions adopted for the passes of a two high stand rolling sequence.

3.7 Mechanical properties of metals

Forces and deformations during the hot metal forming depend upon mechanical properties of processed materials, which in their turn depend upon the nature (chemical composition, structure) of metal as well as upon the deformation conditions (temperature, degree and rate of deformation)[31].Prediction of deformation and mechanical properties in hot rolling is of importance to field engineers in order to manufacturing high quality and quality products. Plastic deformation of metal causes not only the change of shape and sizes of mild steel bloom during the process of hot plastic working (rolling), but also the change of physical-mechanical as well as chemical properties of the metal [31].The deformation is conducted in heated state for decreasing the strain resistance and increasing the plasticity of the worked metal. Forces and deformations during the hot metal forming depend upon mechanical properties of processed materials, which in their turn depend upon the nature (chemical composition, structure) of metal as well as upon the deformation conditions (temperature, degree and rate of deformation).Strength, elasticity, plasticity, impact strength and hardness are concerned to be the mechanical properties. The strength of the metal is interpreted as its ability to stand without damages applied loads at which the internal in stresses metal do not exceed some limit value for the given metal. This value is called ultimate strength or ultimate resistance[31]. The large differences in elastic modulus between the work roll and the bloom causes the work roll to behave as a virtually rigid material. The thermo-physical properties of the bloom and the steel work roll are taken from Biswas (2011).

In general to work out a model for the hot rolling process the data have been used as input parameters for deformation simulations of hot rolling mill using abaqus software given as follows.

Parameters of the process	Values
Bloom material type	Carbon Steel-ASTM,A36 (mild steel)
Bloom cross section	320x320mm^2
Bloom length	3000mm
Input bloom temperature	1000°C-1300°C
Initial temperature of rollers	50°C-100°C or
Roller Diameter	800mm-950 mm **(**920mm)
Rolling speed	60 RPM

Heat transfer coefficient in air (W/m^2K)	10
Heat transfer coefficient in deformation(Wm^2/K	10,000
Coefficient of friction(μ)	0.25,**0.30**,0.35,0.40,0.45,0.50,0.55,0.60,0.65,0.7
Roll material type	Absolutely Rigid

Table3. 2: Input Parameters for deformation simulations of hot rolling mill using abaqus software.

Hot rolling is one of the most important and complex deformation processes in steel manufacturing. Metal forming phenomena, such as plastic deformation, recrystallization, and recovery, occur during the hot rolling to endow metal with expected microstructure and mechanical properties. The careful control of processing as well as material variables during hot rolling can be used to generate materials with better mechanical properties.

Property	Value
Modulus of elasticity (E)	200,000x$10^5 MPa$ -210,000x$10^5 MPa$
Shear modulus (G)	$E/[2(1+\mu)] = 0.769x10^5 MPa \quad for \quad \mu = 0.3$
Yield strength	250MPa
Ultimate strength	400MPa-500MPa
Deformation resistance@ 1000℃	120MPa
Strain-hardening exponent	0.21
Strain rate of exponent	0.13
Poisson's ratio μ	
i. Elastic range	0.3
ii. Plastic range	0.5
Unit mass of steel, ρ	7800 kg/m^3
Coefficient of thermal expansion,σ_t	12x10^{-6}/℃
Brinell hardness number	150-190
Vickers hardness number	157-190
Approximate melting point	1530℃

Thermal conductivity	143.4 W/m
Material	Carbon-steel
Surface emissivity	0.8

Table3.3 :Materials and Mechanical properties of ASTM A36 mild steel or structural steel.

Carbon is the main element influencing the steel properties. The increase of carbon content in steel causes the decrease of plasticity and strain resistance increases.

ASTM A36(mild steel)	C	Mn	Si	S	P	Cu	Fe
	(0.28)%	(0.6-0.90)	0.25%	0.05%	0.04%	0.2%	98.0%

Table3. 4 : Chemical composition of ASTM A36 (mild steel)

Temp(K)	Specific heat(J/(kgÆK))	Thermal conductivity	Density (kg/m3)	Heat transfer CoefficientW/(m2 K)	Elastic modulus (GPa)	Poisson's ratio	Thermalexpansion coefficient[	Yield stress (MPa)
273-473	480-520	45-60	7850-7880	17.3-15.9	200-210	0.28-0.30	1.20-1.10	315-380

Table3. 5 : Temperature dependent properties of ASTM A36 carbon steel.

3.8 Basic Concepts in Rolling Process and Geometrical Relations

At the heart of the rolling operations the process during which the plastic steel passes between at least two rotating rolls (right circular cylinders). In a most accustomed configuration the axes of rolls are parallel and lie in the same plane, so called "exit plane". Clockwise rotation of one roll and the simultaneous counter-clockwise rotation of the other roll are maintained by motor drive via set of spindles. Processed bloom is drawn into the deformation zone by the friction forces developing along the contact interface between the rolled steel and the rotating rolls. A sketch of a rolling pass is depicted in Figure 3.9.

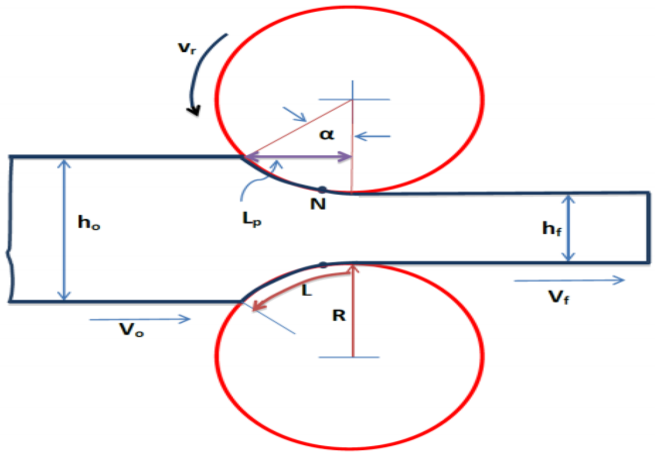


Figure3. 9 : Side views of the deformation zone [bloom]

Before the rolling can commence; steel has to be re-heated in special furnaces to temperatures of deformation. Process that follows can be generally described as a sequence of rolling passes where by the vertical cross-section area of the rolled cylinder is gradually decreased. To enable this series of passes, rolls are assembled within so called housing. Housing is a major frame within a more complex assembly called rolling mill stand. Rolling mill stand is equipped with a mechanism which allows for changing the height between the passes. In order to discuss the basic principles of rolling, we shall analyses relations during the single passing through a gap of rolls. Single rolling pass will occur when the horizontal resultant of friction force overcomes the horizontal resultant of the steel deformation force.

3.9 Mechanism of Roll Bite

Depending on the conditions under which the metal is introduced into the roll gap two situations can occur: - (1) the metal is gripped by the rolls and pulled along into the roll gap and (2) The metal slips over the roll surface. The factors which decide the behavior of metal in the roll gap are the magnitude of the angle of bite, and the ratio of this angle to the friction angle. The size of the frictional force depends on the condition of the surfaces in contact (the rougher the surfaces the greater the frictional force) and on the velocity of slip and the roll pressure. By the third law of dynamics, which states that every action has an equal and opposite reaction, metal introduced between the rolls exerts a pressure on the rolls at the point of contact, and the rolls act on the metal with an equal and opposite reactive force. For the work piece to enter the throat of the roll, the component of the friction force must be equal to or greater than the horizontal component of the normal force. For the work piece to enter the throat of the roll, the component of the friction force must be equal to or greater than the horizontal component of the normal force[38].

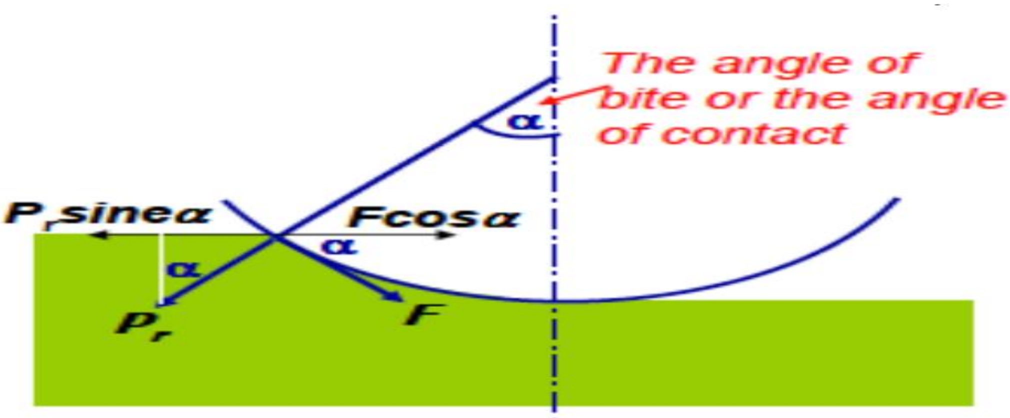


Figure3. 10 : Roll bite condition

$F\cos\alpha = P_r \sin\alpha$ $\frac{F}{Pr} \geq \frac{\sin\alpha}{\cos\alpha} \geq \tan\alpha$ It is known that $F = \mu P$ or $\mu = \frac{F}{P_r} = \tan\alpha$**,** μ= $\tan\alpha$

F is a tangential friction force & P_r $is\ radial\ force$, If tan a > μ, the work piece cannot be drawn. If μ = 0, rolling cannot occur. The maximum angle of α at which free rolling can take place without using force to push the metal into the roll gap is called the maximum angle of bite. The usual values of biting angles employed in the metal working industry are: 2–10° for cold rolling of sheets and strips; 15–20° for hot rolling of sheets and strips; 24–30° for hot rolling of heavy billets and blooms. Maximum reduction from triangle ABC, we have[39]

$$\mathbf{R^2 = L^2{}_p(R - a)^2} \tag{3.11a}$$

$$L^2{}_p = R^2 - (R^2 - 2Ra + a^2) \tag{3.11b}$$

$$L^2{}_p = 2Ra - a^2 \cong 2Ra \tag{3.11c}$$

As a is much smaller than R, a^2 can be neglected

$$L_p \cong \sqrt{2Ra} \approx \sqrt{R\Delta h} \tag{3.12a}$$

$$\mu = \tan\alpha = \frac{L_p}{R - \frac{\Delta h}{2}} \approx \sqrt{\frac{\Delta h}{R}} \rightarrow \Delta h_{max} = \mu^2 R\ Maximu\ reduction\ in\ thicknes \tag{3.12b}$$

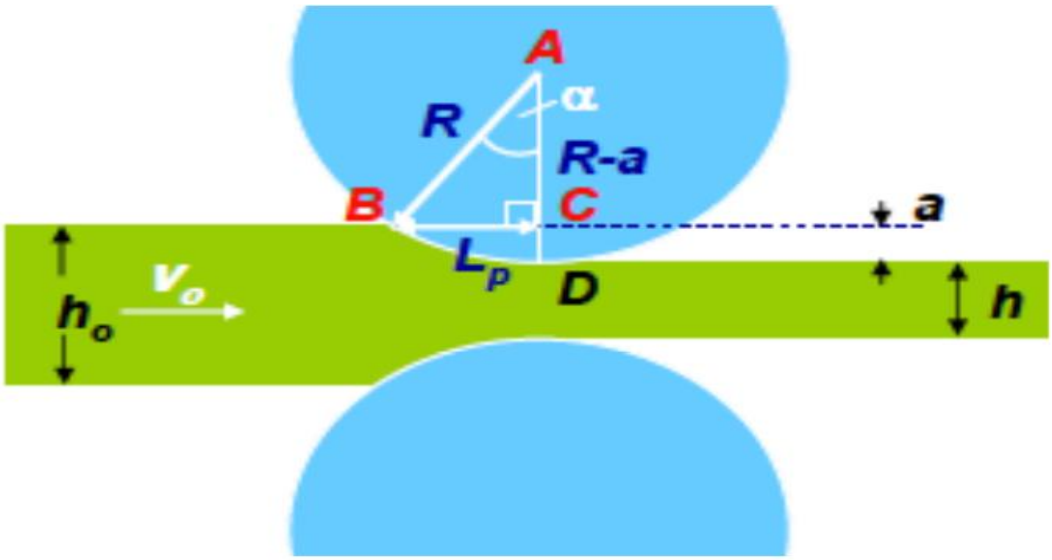


Figure3. 11: Roll bite maximum reduction condition

3.1.1 Friction and Contact Conditions

Friction is one of the important parameters in metal forming processes since it affects metal flow in the rolling, forming load, strain distribution, roller life, surface quality of the product etc. The range of coefficient of friction in different metal forming applications is not well known and the factors affecting variation are ambiguous. Commercially available FEA packages input the coefficient of friction as constant among the whole process which is not a realistic approach[40].The friction and contact conditions in this section are described between two boundaries that belong to the rigid and deformable bodies or friction, in a simple manner, can be described as "surface resistance to the relative sliding or rolling motion" while in metal forming operations this term converts to work piece-roller surface resistance to metal flow. Although several different methods have been presented in describing the macroscopic contact and friction phenomena within the framework of continuum mechanics, the method of point wise description of friction and contact conditions has been used in most practical applications. The contact condition and friction can be summarized as flows [41]:

3.1.2 Numerical (Mathematical) Aspects of Contact modeling

When modeling contact phenomenon in a problem, such as in the hot rolling process, boundary conditions such as friction factor, contact area, contact pressure and material properties on the\ contact interface are changed during the process; therefore, the numerical simulation of contact phenomenon is a non-linear problem. Boundary non-linear (BNL), which is so called contact problem, needs to be well defined, that is, the numerical characters of the interface friction condition should be defined properly. In the hot metal deformation, the interfacial friction condition has significant influence on deformation, and cannot be measured precisely[42].The simulation of many physical problems requires the ability to model the contact phenomena. The analysis of contact behavior is complex because of the requirement to accurately track the motion of multiple geometric bodies, and the motion due to the interaction of these bodies after contact occurs. This includes representing the friction between surfaces and heat transfer between the bodies if required. The numerical objective is to detect the motion of the bodies, apply a constraint to avoid penetration, and apply appropriate boundary conditions to simulate the frictional behavior and heat transfer. Contact problems categorized into two domains; the first is when a deformable body makes contact with a rigid surface and the second is when a deformable body makes contact with another deformable body or itself [43]**.** Contact, by nature, is a non-linear boundary value problem. During contact, mechanical loads and sometimes heat are transmitted across the area of contact. If friction is present, shear forces are also transmitted. Boundary contact conditions cause huge difficulties and make the convergence of the model extremely difficult. It is necessary to match the initial geometric shape as well as possible, but also to introduce test to determine when a node comes into contact with a rigid or elastic tool. This can be done geometrically, and the node then restored to the surface if it has apparently crossed the boundary. It is then necessary to determine whether the normal force has become tensile, before re-sitting the node[44]. Contact can be defined as finding the displacement of points A and B such that

$$(\overline{u}_A - \overline{u}_B).n = TOL \tag{3.13}$$

Where A is on one body and B is on another body, n is the direction cosine of a vector between the two points, and TOL is the closure distance.

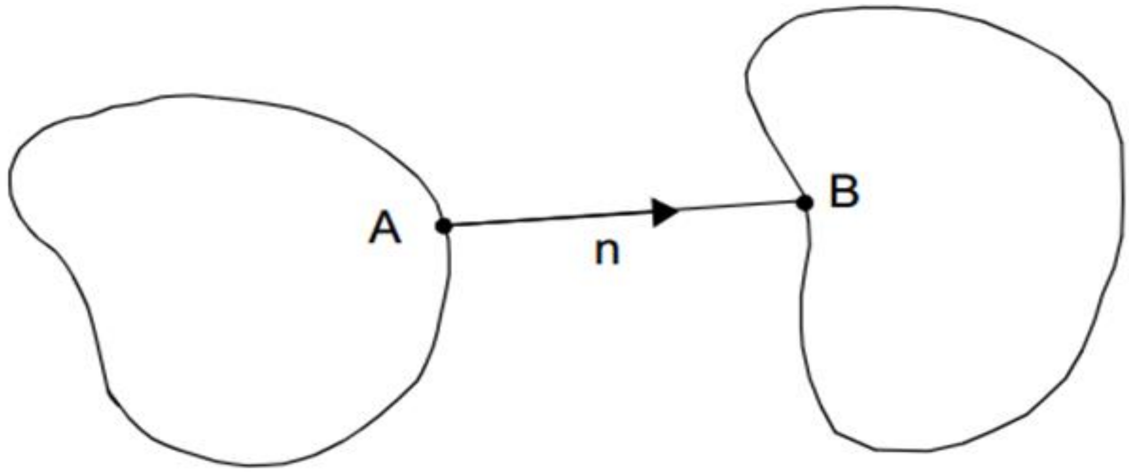


Figure3. 12 : Normal gaps between potentially contacting bodies

Contact problems are commonly divided into two domains:

a) A deformable body makes contact with a rigid surface; b) A deformable body makes contact with another deformable body or itself. The contact situations that used in our study of the rolling problem: deformable to rigid body contact.

3.1.3 Deformable-Rigid Contact

The deformable rigid contact used in this case where the work piece is modeled as a deformable element but the rolls are modeled as a rigid body. This method is computationally inexpensive and it is the one used in most cases in this thesis. In such a problem, a target node on the deformable body has no constraint while contact does not occur. Once contact is detected, the degrees of freedom are transformed to a local system and a constraint is imposed such that [19,27, 49]

$$\Delta\overline{u}_{normal} = \overline{v}\,.\overline{n} \qquad (3.41)$$

Where v is the prescribed velocity of the rigid surface. This local transformation is continuously updated to reflect sliding of point **A** along the rigid surface. If the contact is glue contact, an additional displacement constraint is activated or if the glue option is activated, an additional displacement constraint is formed as [46].

$$\Delta\overline{u}_{tangential} = \overline{v}\,.\overline{t} \qquad (3.15)$$

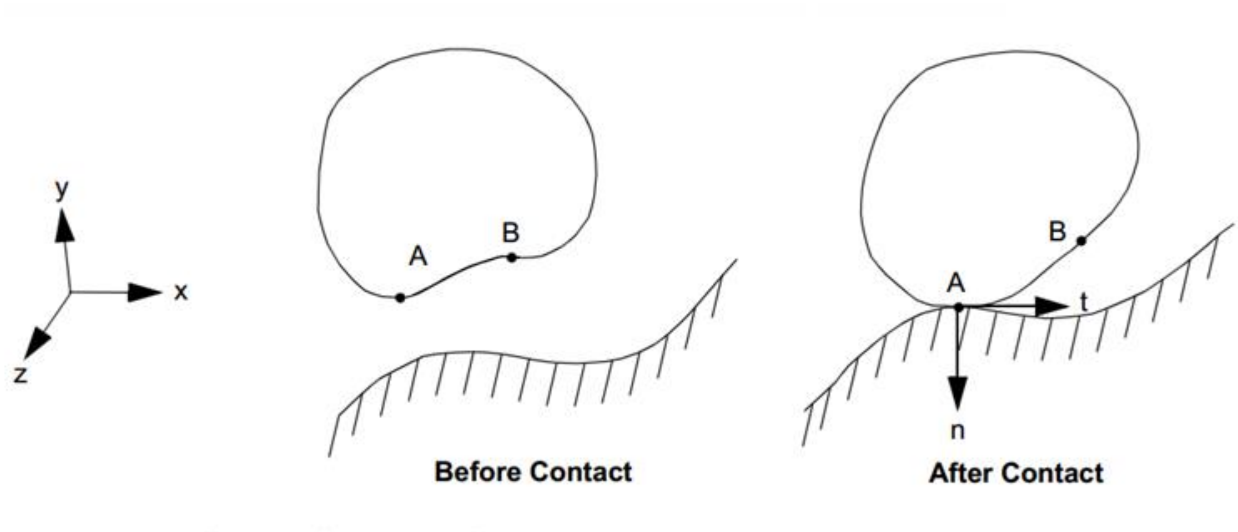


Figure3. 13 :Contact Coordinate Systems

3.1.4 Contact Detection

The determination of when contact occurs and the calculation of the normal vector are critical to the numerical simulation. The procedure used by MSC Marc is as follows: In the deformable to rigid body contact case, the contact procedure has three cases:

Case 1: Contact not detected when

$$\Delta\overline{u}_A.\overline{n} \ < |D-d| \tag{3.16}$$

In this case node A does not touch the rigid surface so no constraint is applied

Case 2: Contact detected when

$$|\Delta\overline{u}_A.\overline{n}-d| \leq D \tag{3.17}$$

In case 2a node A is near the rigid body within tolerance and contact constraint pulls node A to contact surface if F < F_s In case 2b node A penetrates within tolerance and the contact constraint pushes node A to contact surface.

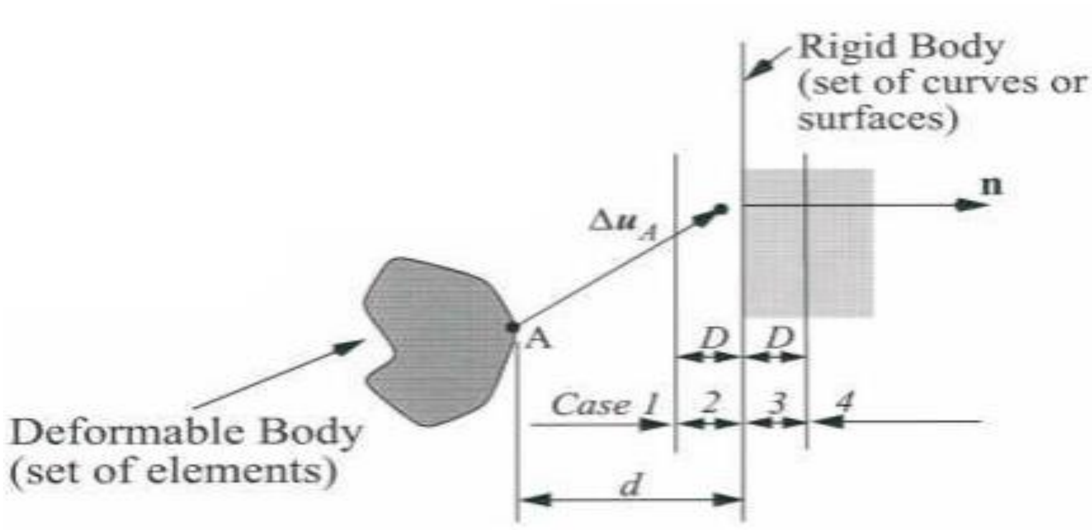


Figure3. 14: Deformable to Rigid Body Contact Procedure MSC Software Corporation

Where v =the prescribed velocity of the rigid surface, $\Delta\overline{u}_A$ = incremental displacement vector of node A, $\overline{n}$= unit normal vector with proper orientation, $\overline{t}$= unit tangential vector, D=contact distance, F_s =separation force, TOL=contact closure distance.

Case 3: Penetration detected when

$$\Delta\overline{u}_A.\overline{n} > |D + d| \tag{3.18}$$

In this case node A penetrates out of tolerance and increment gets split (loads reduced) until no penetration occurs. By default, in most models, the contact tolerance is equally applied to both sides of a segment. This can be changed by introducing a bias factor B such that $0 \leq B \leq 1$.

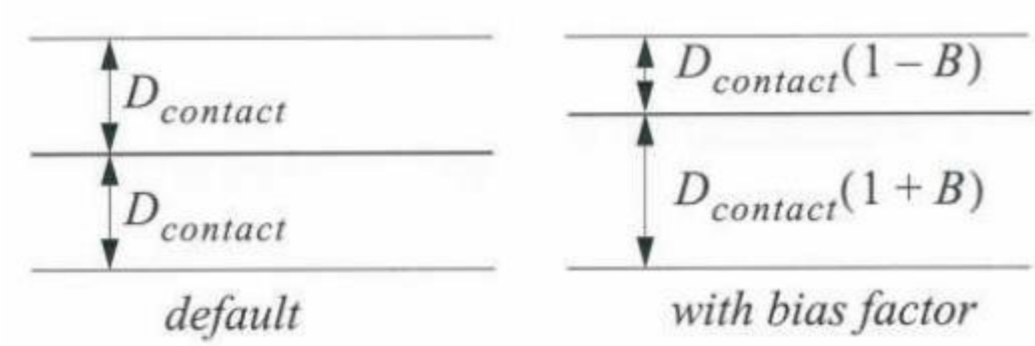


Figure3. 15 : Bias factor MSC Software Corporation

Choosing a bias factor > 0 may be useful to reduce increment splitting since the distance to cause penetration is increased, and to improve accuracy, since the distance below which a node comes into contact is reduced.

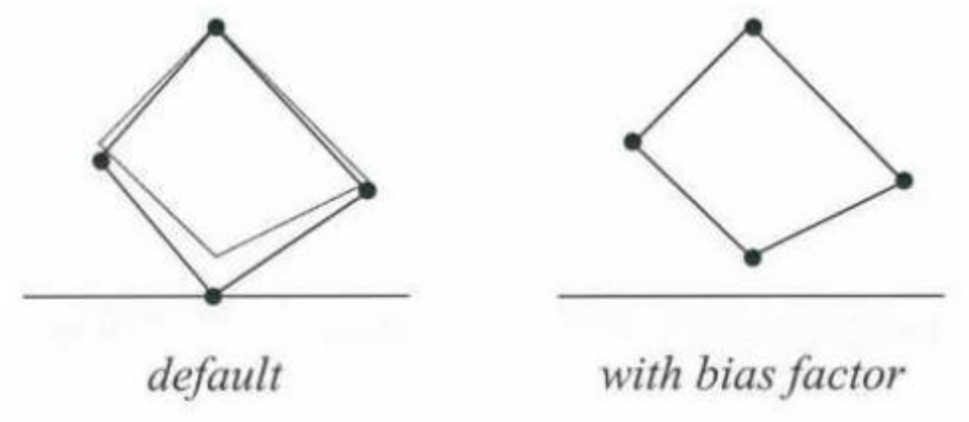


Figure3. 16: Bias factor comparison MSC Software Corporation

The contact condition can be summarized as: Any material particle of a given body cannot penetrate into another, the normal component of contact traction must be compressive for each body, a pair of contact points can separate only when the contact traction vanishes or becomes tensile

3.1.5 Friction Modeling in Rolling

Friction occurs everywhere, including human acts, many things depend on friction. Usually friction presents in machines parts during the operation. Friction is not required almost everywhere, so a great deal is done to reduce it by control or by design. Friction is often quantified by a coefficient of friction (μ), expressing the ratio of the friction force to the applied load. It is a very complicated phenomenon arising from the contact of surfaces of two bodies. The boundary conditions to be satisfied by the solution of the equations of the mechanical component of the model of the flat rolling process include the friction stress at the roll-strip interface as well as the shape of that interface [47].The movement of one component relatively to another one, both pressed together by some load, a force is necessary. The amount of force depends on the surface conditions of both parts and on the coefficient of friction between the two partners [48].The resistance occur or originated during displacement of one solid along the surface of the other is called contact friction or external. The force that resist the relative displacement of solids is called friction force [31].Friction, in a simple manner, can be described as "surface resistance to the relative sliding or rolling motion while in metal forming operations this term converts to "work piece-roller surface resistance to metal flow. Due to the highly non-linear behavior, contact modeling remains among the more difficult disciplines within finite element simulations. Contact between work pieces and tooling and in-between work pieces define the shape of formed components in metal forming. Descriptions of the contact between a deformable work piece and rigid tools are given based on mechanical contact while thermal contacts are included by simplification of the mechanical description**.** The mechanical contact conditions can be separated into normal constraints and tangential constraints. The normal constraint is always that the contacting surfaces cannot penetrate into each other. The tangential constraints depend on the treatment of friction. In case of a frictionless approach, there are no tangential constraints and in case of full sticking, the tangential constraints are similar to the normal constraint since relative sliding is not allowed. In case of frictional conditions (including combined sticking and sliding), the constraints are governed by the employed friction law. Whenever two solid bodies move over each other the phenomenon of friction occurs, i.e. a force resisting the relative movement of the bodies. If a resultant force acts on the base of a rigid body, then to move the body a certain force is required to overcome the frictional resistance between the base of the body and the plane on which it rests [49]. The resistance that is encountered when two bodies are rubbed against each other is called friction. Friction is an important factor in metal forming. It dissipates energy and hence increases the force needed to deform a material. It generates heat, which complicates the control of the deformation temperature. It can affect the material flow during deformation and leads to inhomogeneous deformation. The friction between the metal and rolls affects the forming process, increase the required load for forming, reduce the surface quality and increase the wear of tools [38]. The first 'recorded' recognition of friction came from Leonardo da Vinci (Schey [1970]). The subject was rediscovered by Amontons (Amontons [1699], Schey[1970], Moller and Boor [1996]). Friction coefficient was postulated by Amontons and Coulomb (Coulomb [1785], Schey [1970], Moller and Boor [1996]) as proportional to the normal force and independent of contact area and relative speed of the moving surfaces [50]. Friction is a complex physical phenomenon that involves the characteristics of the surface such as surface roughness, temperature, normal stress, and relative velocity[51]. The actual physics of friction continues to be a topic of research. Hence, the numerical modeling of friction has been simplified to three idealistic models [19].

3.1.6 Stick-Slip Friction Model (Stick-slip (Modified Step Function) Model)

In sticking contact there is no sliding between the surfaces in contact, based on this the Coulomb model of friction models is the transition from stick to slip. Discovered by Leonardo da Vinci in the 15th century, and verified by experiments by Charles A. Coulomb in the 18th century, this stick slip friction model uses a penalty method to describe the step function of Coulomb's Law [43].

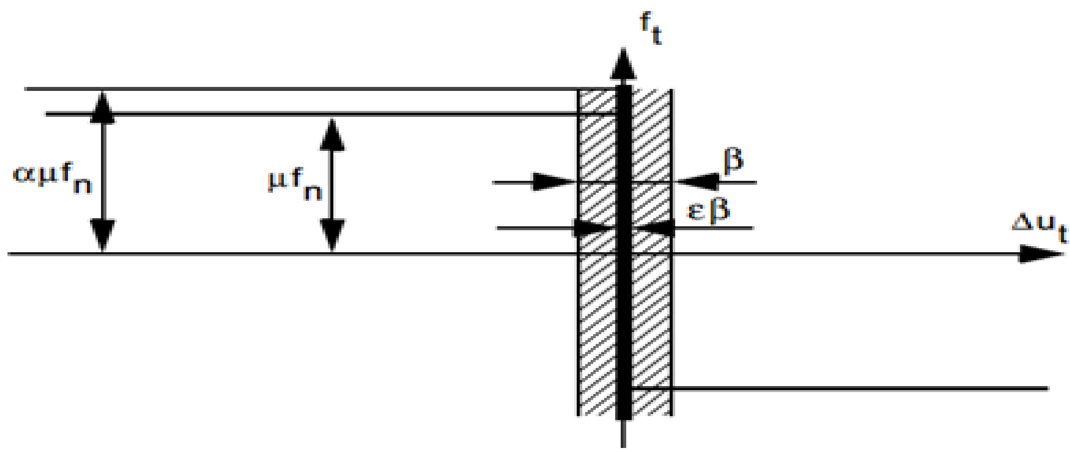


Figure3. 17: Modified Step Function or Stick-slip Friction Parameters.

With $F_t \leq \mu F_n$ *static* and $F_t \leq \alpha\mu F_n$ *kinetic* where $F_t =$ *tangential force(friction force)*, $F_n =$ *normal reaction*, $\Delta u_t =$ incremental tangential displacemen ,$\beta =$ stick to slip transition region, $\alpha =$ coefficient multiplier and ε =small constant→ 10^{-6} *so that* $\varepsilon\beta \to 0$.

3.1.7 Adhesive Friction or Coulomb Sliding Friction Model

An adhesive model of friction in which the friction stress is based upon the coefficient of friction and the equivalent normal stress at the surface. The most commonly model used and the one used in this work to model the friction between the work piece and the rolls [43] Coulomb sliding friction model is:

$$\sigma_{fr} \leq -\mu\sigma_n . t \qquad (3.19)$$

σ_n= normal stress, σ_{fr}=tangential/shear friction stress, μ= friction coefficient and t= tangential vector in the direction of the relative velocity.

$$t = \frac{v_r}{|v_r|} \tag{3.20}$$

$v_r = relative\ sliding\ velocity.$

The Coulomb model is also often written with respect to forces

$$f_t \leq \mu f_n . t \tag{3.21}$$

Where $f_t = tangential\ force, f_n = normal\ reaction$

For a given normal stress, the friction stress has a step function behavior based upon the value of, $v_r or\ \Delta u$.

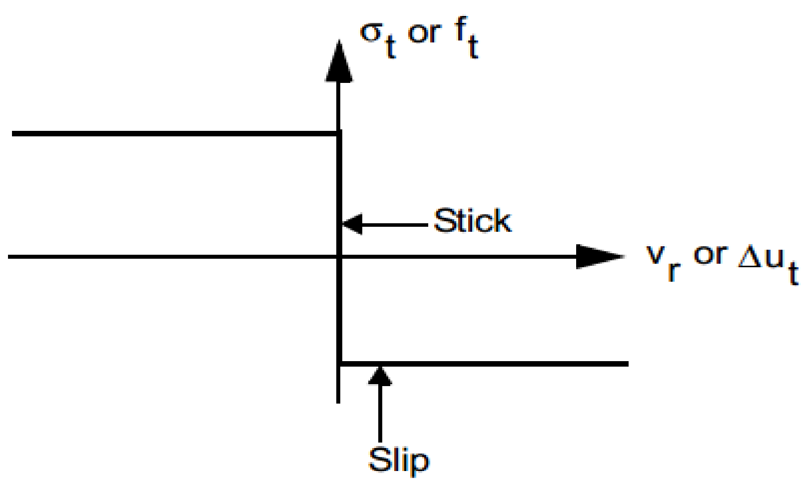


Figure3. 18: Coulomb Friction Model.

Since this discontinuity in the friction value may easily cause numerical difficulties, different approximations of the step function have been implemented. They are graphically represented in Figure and they will be successively discussed[51].

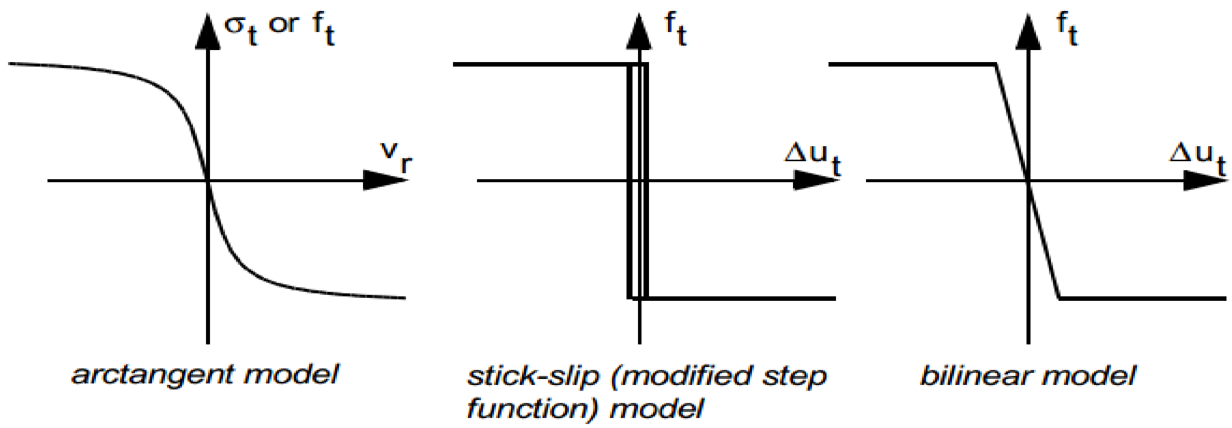


Figure3. 19 : Different Approximations for the Coulomb Friction Model

$$\sigma_{fr} \leq -\mu\sigma_n \frac{2}{\pi} arc\tan\left(\frac{v_r}{|v_r|}\right).t \tag{3.22}$$

Physically, the value of v_r can be seen as the value of the relative velocity below which sticking occurs. The value of $|v_r|$is important in determining how closely the mathematical model represents the step function, as shown in Figure. A very large value of $|v_r|$ results in a reduced value of the effective friction. A very small value may result in poor convergence. It is recommended that the value of be 1% to 10% of a typical relative sliding velocity $|v_r|$.

In terms of the tangential and normal force

$$f_t \leq -\mu f_n \frac{2}{\pi} arc\tan\left(\frac{v_r}{|v_r|}\right).t \tag{3.22}$$

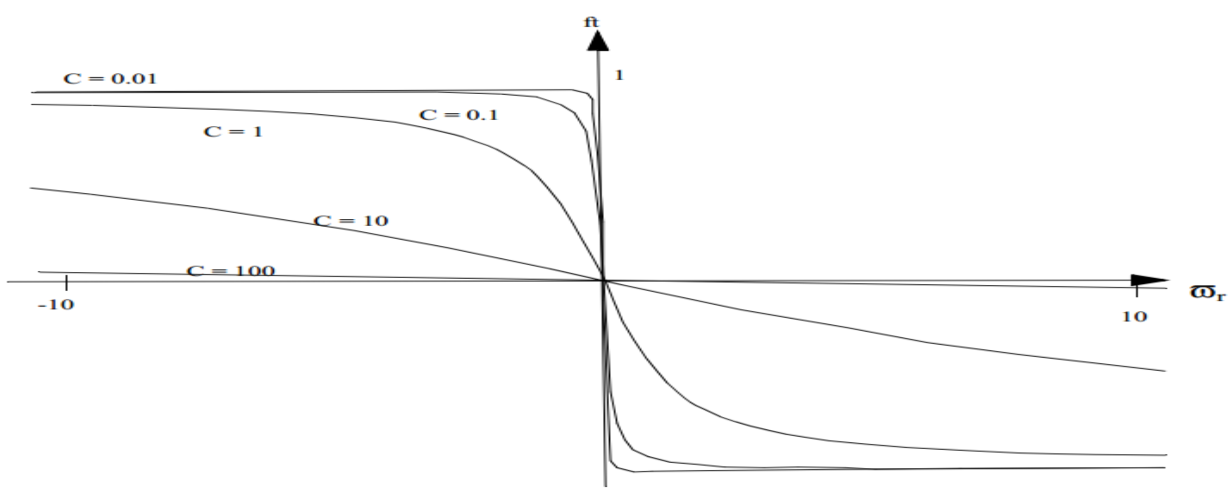


Figure3. 20 : Force based Coulomb model approximation (fn=1, C=|vr |).

Coulomb friction is a highly nonlinear phenomenon dependent upon both the normal force and relative velocity. Incidentally, this is the model used by Chen and Kobayashi in which the frictional forces are dependent on the velocity and also the one used in this thesis. Therefore, for the finite element models shown in this work, $\sigma_{fr} \leq -\mu\sigma_n \frac{2}{\pi} arc \tan\left(\frac{v_r}{|v_r|}\right)$is is the friction stress[52].

3.1.8 Shear (Sliding) Friction Model: is proposed a general friction model resembling the two above laws at low and high normal pressures and providing a transition in-between the above Fig53. The Coulomb friction model sometimes does not correlate well with experimental observations when the normal force/stress becomes large. If the normal stress becomes large, the Coulomb model might predict that the frictional shear stresses increase to a level that can exceed the flow stress or the failure stress of the material. As this is not physically possible, the choices are either to have a nonlinear coefficient of friction or to use the cohesive, shear based friction model. The shear based model states that the frictional stress is[42,49] a fraction of the equivalent stress in the material:

$$\sigma_{fr} < \mu \frac{\overline{\sigma}}{\sqrt{3}} \ (stick) \ \text{ and } \ \sigma_{fr} - \mu \frac{\overline{\sigma}}{\sqrt{3}} t \ (slip) \tag{3.23}$$

Again, this model is implemented using an arctangent function to smooth out the step function:

$$\sigma_{fr} \leq -\mu \frac{\overline{\sigma}}{\sqrt{3}} \frac{2}{\pi} arc \tan\left(\frac{v_r}{|v_r|}\right) . t \qquad (3.24$$

With $\mu(x , f_n, T, v_r, \overline{\sigma})$=friction coefficient where:-X= position of the point at which friction is being calculated, f_n =normal force at the point at which friction is being calculated,T =temperature at the point at which friction is being calculated, $v_{r=}$ relative sliding velocity between point at which friction is being calculated and a surface $\overline{\sigma} =$ flow stress of the material.

A contact analysis has several consequences on performing a coupled analysis. When performing a coupled contact analysis between multiple deformable bodies; each body deforms due to mechanical and thermal loads and undergoes heat conduction. When the bodies come into contact, there is heat flux across the surfaces. You need to provide a coefficient of heat transfer between the surfaces. This is often quite significant as a hot work piece might come into contact with a cold tool set. The heat rate generated due to friction is expressed by [43]

$Q_{fr} = f_{fr} v_{r.} M_{eq}$ (3.25)

Where $M_{eq} = (is\ the\ mechanical\ equivalent\ of heat)$fraction of friction energy that is converted to heat, f_{fr} =friction force, $v_{r.}$ =relative roll-work piece sliding velocity

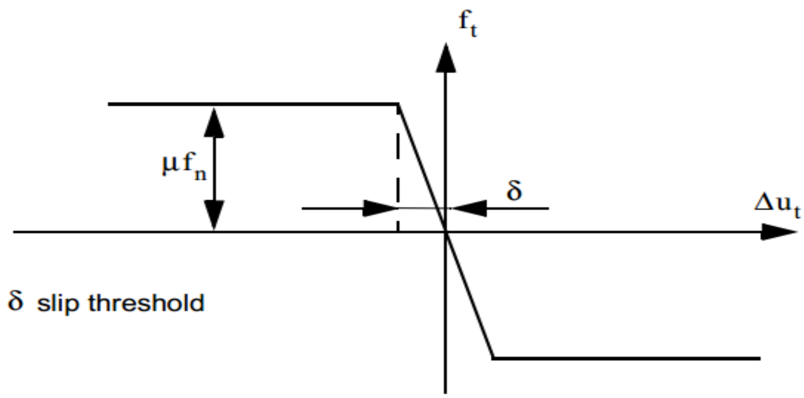


Figure3. 21: Shear Friction Model.

The Friction condition can be summarized as:

The magnitude of the tangential component of contact traction must be less than or equal to that of the normal component multiplied by a coefficient of friction. The instantaneous relative motion in the tangential direction for a pair of contact points can take place when the equality in (a) above holds. The tangential relative motion must be along the same line as the tangential component of contact traction but in the opposite direction.

3.1.9The thermo-mechanical modeling of flat rolling

The thermo-mechanical analysis has been carried out employing an incremental procedure in order to follow the whole transient process from the work piece input phase to the achievement of steady-state conditions; at each step of the deformation path a staggered approach is used, which consists first of an heat transfer analysis and subsequently a mechanical one, where the work piece and the rolls properties are evaluated on the basis of the temperature field [3].The definition of coupled systems includes the multiple domains and independent or dependent variables describing different physical systems. In the situation with multiple domains, the solution for both domains is obtained simultaneously. The challenge in modeling this process is that a coupling between the thermal history and the mechanical behavior of the material during rolling pass occurs [53]. For the applications studied, thermo-mechanical coupling is not very strong so rather than directly solving the full (ε, T, v, p) problem, which increases very significantly the problem size, equations are solved in an iterative manner until convergence. Similarly, the dependent variables cannot be condensed out of the equilibrium equations explicitly. Coupled systems can be classified into two categories [54]: Interface variables coupling occurs through the interfaces of the domain. The domains can be physically different (for example, fluid-solid interaction) or physically the same but with different discretization (for example, mesh partition with explicit procedures in different domains).Field variables coupling occurs through the governing differential equations describing different physical phenomenon; for example, the coupling between the thermal and mechanical problems takes place through the temperature-dependent material properties in the mechanical (stress) problem and the internal heat generation in the mechanical problem caused by plastic work, which serves as input for the heat transfer problem. The temperature distribution and displacements are obtained [54].Under the operations that performed in the metal forming industry (such as casting, extrusion, rolling, and stamping) can require a coupled thermo-mechanical analysis that we can observed physical phenomena must be modeled by a coupled analysis if the following conditions pertain: The body undergoes large deformations such that there is a change in the boundary conditions associated with the heat transfer problem. Deformation converts mechanical work into heat through an irreversible process which is large relative to other heat sources. In either case, a change in the temperature distribution contributes to the deformation of the body through thermal strains and influences the material properties [54].There are two primary causes of coupling. First, coupling occurs when deformations result in a change in the associated heat transfer problem and such a change can be due to either large deformation or contact and the second cause of coupling is heat generated due to inelastic deformation. Mathematical models of the flat rolling process are numerous [55]. In each, the equations of motion, thermal balance, material properties and roll deformation are used to calculate the stress, strain, strain rate, velocity and temperature fields, the roll pressure distribution, roll separating forces and roll torques**.** The accuracy of these models depends on the quality of the assumptions made. In the conventional models, most researchers assume the existence of homogeneous compression of the work materials, considered to be made of an isotropic and homogeneous material that is incompressible in the plastic state. Further, plane strain conditions are assumed to exist and either a constant friction factor or Coulomb friction conditions apply at the roll-work piece interface. Assumptions and simplifications vary broadly when finite element methods are employed [11,12]. As far as rolling is concerned, a general or complete mathematical model of the flat rolling process should include [29,70]**:** Equations of motion of the deformed metal, Heat balance of the roll/work piece system, equations of equilibrium of the work roll, description of the frictional forces between the work roll and the metal, Description of the material properties [47]. A general mathematical model of the flat rolling process may be formulated following the discussion above. As the work piece enters the roll gap it is first deformed elastically. It speeds up; the relative velocity between the roll and the work piece is such that friction draws the metal in. The criterion of plastic flow governs the manner in which the transformation from elastic to plastic happens in what is known as the elastic-plastic interface. The work piece proceeds through the roll gap and more plastic flow occurs until finally at the exit roll pressure is removed. It is observed that during rolling, the relative velocities of the roll and the rolled metal change and as the rolled metal is accelerating forward it reaches the roll surface velocity at the no-slip or neutral point. From then on, as further compression occurs, the bloom speeds up and the direction of friction changes in such a way that it now retards motion. Exit velocity of the bloom is often larger than that of the roll and the difference between the two velocities is determined by the forward slip [3,11,12,65]**.**Thermal events occurring during the bloom passage through the roll gap are also of importance. In fact, it is the thermal events that contribute most to the metallurgical developments of the final structure of the rolled material. Surface conditions, roll wear and thus roll life are also affected by thermal conditions. Heat is generated because of the work done on the rolled metal, increasing its temperature. Interfacial friction forces also cause the temperature to rise. Contact with the cold and often water-cooled rolls also causes heat losses. Metallurgical transformations also contribute to temperature changes. A complete mathematical model should account for both thermal and mechanical events, which occur in the deformation zone during the rolling process [12,13]**.**Several assumptions regarding material behavior must be made. The material is usually assumed to be, and to remain, isotropic and homogeneous; it is considered to be elastic-plastic even though as gross plastic straining takes place, elastic deformations may be quite small in comparison to plastic strains. During forming the volume of the plastic region is taken to remain constant, and finally, a plane state of strain is assumed to exit [58]**.** In this chapter we will study the governing equations and boundary conditions for the mechanical problem portion of the rolling problem. Then, we will study the heat transfer and thermal balance problem looking at the five sources of heat transfer as well as the heat transfer boundary conditions involved in the hot rolling problems. Finally, we will take a look at the main classical mathematical rolling model, developed by von Karman. We will study the mathematical aspects of the complicated contact problem, paying attention to the rigid-deformable cases. The friction problem and its influence in the rolling problem will then be examined. Later in this chapter, we will take a look at the main theory of plasticity issues, and the material model used in this thesis for the hot rolling problems. Thermo-mechanical modeling of hot rolling mild steel (bloom)is a fully coupled problem that is highly non-linear because of the interactions between temperature, strain and strain rate and applied to the initial material leads to semi or final products characterized by new, better properties (with respect to the initial material).So an integrated mathematical model of thermo-mechanical behavior of the hot rolling process are employed to determining the effects of various rolling parameters on the thermo-mechanical behavior of the rolled metal during rolling process by applying proper boundary conditions which help us to solve the equation governing thermo-mechanical coupled problem.

By having a great understanding of the physics of the thermo-mechanical coupled problem we can then model these physics into our model second order linear homogeneous partial differential equation for the thermal portion of the problem, together with the boundary and initial conditions constitutes a thermal initial boundary value problem which we will solve using a variational approach that will be implemented into the finite element formulation. The mechanical portion of the problem leads to another set of partial differential equation given by the equilibrium conditions, the compatibility conditions, the constitutive equations, and the yield criterion, which together with the boundary conditions, lead to a mechanical initial boundary value problem whose solution is obtained through a variational approach that requires among the admissible velocities vi that satisfy the conditions of compatibility and incompressibility, as well as the velocity boundary conditions, the actual solution gives the mechanical functional a stationary value .The final solution to our problem will be determined by the simultaneous solutions of these two initial boundary value problem due to the strong coupling between the mechanical and the thermal problems. There are two primary causes of coupling. First, coupling occurs when deformations result in a change in the associated heat transfer problem. Such a change can be due to either large deformation or contact. The second cause of coupling is heat generated due to inelastic deformation. The irreversibility of plastic flow causes an increase in the amount of entropy in the body, which in turns results in changes to the associated mechanical problem.

3.2.1 Mechanical Initial Boundary Conditions.

The success of a mathematical model is measured by its predictive ability. The mathematical description of the problem is not complete until boundary conditions have been properly specified during the deformation process; the boundary conditions of the solid must be modified. Boundary conditions in the rolling process include friction stresses on the contact surface, the shape of that surface and tensions at the entry and exit regions [55]. This is typically the case when a part of the solid boundary comes into contact with another solid, such as a roller in metal forming processes: if this occurs, the new boundary conditions must take account of the contact stresses (pressure and friction) between both solids [59].The mechanical boundary value problem is governed by equilibrium equations; von Mises yield criterion, flow rule, and constitutive equations. Boundary conditions are assigned to rolls velocity and surface tractions on the rolls-work piece contact interface. Contact properties are defined as a stick-slip numerical model based on the Coulomb friction model [22]. Realistic analysis of the flat rolling processes means that the events taking place during a pass should be looked at a coupled thermo-mechanical problem [55]. Arbitrary separation of these components may lead to erroneous appreciation of the variables and parameters that characterize the process and will be able to properly take into account the following combined phenomena includes [70,75]:- heat generation due to plastic work, heat generation due to friction forces, accumulation of the deformation work connected with an increase of dislocation density, thermal events connected with metallurgical transformations, cooling by air or by water spray on free surfaces, cooling due to contact with the roll. Radiation from the bloom at 1100℃ -1300 ℃ to the environment in the hot rolling. It is of course well known that during hot rolling the metallurgical and mechanical properties of the metal depend strongly on the temperature [55].In order to obtain a solution for stress, strain, strain rate, velocity and temperature fields with in the rolled metal an, appropriate boundary and initial conditions have to be introduced. The mechanical boundary conditions which are given by the prescribed velocities and tractions along the boundary of the roll-work piece interface [19]:Tension & compression tractions, Friction tractions along the contact surface **,**velocity constraints.

The governing equations what we have seen below, the boundary conditions we have just seen, and the initial conditions are part of the mechanical initial boundary value problem which is summarized as follows: Governing equations: Equilibrium equations,Mises yield condition, Flow rule (constitutive equations),Constitutive equations, Boundary conditions: Velocities, tractions (frictional stresses in tangential direction), Initial conditions: Initial velocities, Initial Tractions, This mechanical initial boundary value problem constitutes one half of the overall problem in rolling.

3.2.2 Governing Equations of the Mechanical Problem

As with the earlier development for the deformation analysis, the equations for the thermal analysis of the work piece and the die are developed in Eulerian coordinates. As it is observed there is a complex interconnection between governing equations. In order to solve these equations, the simulation was carried out by a 3D coupled thermo-mechanical FE analysis using commercial finite element software package Abaqus/Explicit. The equation that governs the conditions of equilibrium of plastically deforming rolled metal is the following;-

$$\frac{\partial \delta_{ij}}{\partial x_j} + \rho b_j = \rho \frac{\partial v_j}{\partial t} \quad [3.13a]$$

Where $\delta_{ij} =$ components of the Cauchy stress tensor $b_j =$ components of body forces vector $v_j =$components of velocity vector $\rho =$ density of material. The equation that governs the conditions of equilibrium that plastically deforming stock in the rectangular cartesian coordinate system, are given by the following if the body force is neglected[56].

$$\frac{\partial \delta_x}{\partial x} + \frac{\partial \tau_{yx}}{\partial y} + \frac{\partial \tau_{zx}}{\partial z} = 0 \quad (3.13b)$$

$$\frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \tau_y}{\partial y} + \frac{\partial \tau_{yz}}{\partial z} = 0 \quad (3.13b)$$

$$\frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\delta_z}{\partial z} = 0 \quad (3.13c)$$

3.2.3 Yield Criteria

Different criteria have been proposed for yielding of solids; many of these were originally suggested as criteria for failure of brittle materials and were later adopted as yield criteria for ductile materials. When a metal is under deformation loads that are very high, the metal will start to flow plastically. The conversion of plastic flow from the pure elastic state is known as the yield condition. Yield criteria are the mathematical patterns which are used to predict when yielding takes place under combined stress states in terms of certain properties of the metal being stressed. In simple uniaxial compression or tension, the metal flows or begins deforming plastically when the applied stress a reaches the value of the flow stress. On the other hand, in a multiaxial state of stress, plastic flow or yielding depends on a combination of all stresses. Two major criteria for plastic flow or yielding are well known as Tresca and von Mises criterion of yield (plastic flow). Both criteria pointed out that when the effective stress or equivalent stress reaches the value of the yielding stress a, the metal will start flowing plastically. Plastic deformation is produced by dislocations, which means that materials are incompressible during plastic deformation, and many hydrostatic state of stress does not produce yielding. This implies that shear stresses produce yielding.

3.2.4 Tresca Yield Criterion

Tresca or shear stress criterion assumes that yielding will occur when the maximum shear stress reaches the value of the maximum shear stress occurring under hot rolling. The maximum shear stress is equal to half the difference between the maximum and the minimum principal stress as shown below.

$$\tau_{max} = \frac{(\sigma_1 - \sigma_3)}{2} = k \quad (3.14)$$

Thus, the Tresca yield criterion can be expressed as the plastic flow begins when

$$\sigma_1 - \sigma_3 = \sigma_0 = 2k \quad (3.15)$$

$$2k = \frac{1}{2}\sigma_0 \quad (3.16)$$

Where, σ_1 and σ_3, are the first and third principal stresses, σ_0 , is the yield stress, and k is the shear yield stress of material. The above equation shows that according to Tresca's criterion, plastic flow starts if the difference of maximum, $\sigma_1$and minimum σ_3, principal stresses is equal to yield stress σ_0.The other mechanical boundary value problem is governed by equilibrium equations; the distortion energy theory or von Mises yield criterion, flow rule, and constitutive equations. Boundary conditions are assigned to rolls velocity and surface tractions on the rolls-work piece contact interface. Contact properties are defined as a stick-slip numerical model based on the coulomb friction model.

3.2.4 Plastic Stress-strain Relations

Having discussed the relationships between stress state and plastic yielding, it is now necessary to consider the relations between stress and strain in plastic deformation. In the elastic region the strains are uniquely determined by the tresses through Hooke's law without regard to how the stress state was achieved. This is not the case for plastic deformation. In the plastic region the strains in general are not uniquely determined by the stresses but depend on the entire history of loading. Therefore, in plasticity it is necessary to determine the differentials or increments of plastic strain throughout the loading path and then obtain the total strain by integration or summation [61]. The on the basis of total strain in a large deformation of the specimen can be defined as

$$\epsilon_1 = \int_0^{\epsilon_1} d\epsilon_1 \tag{3.17}$$

$$\epsilon_1 = \int_0^{\epsilon_1} d\epsilon_1 = \int_{l_0}^{l_1} \frac{dl}{l} = \ln\left(\frac{l_1}{l_0}\right) \tag{3.18}$$

Thus, if true strains are used, the equation of constancy of volume for incremental strains, $\varepsilon_1 + \varepsilon_2 + \varepsilon_3$ = 0, may be extended to large strains, as $\varepsilon_1 + \varepsilon_2 + \varepsilon_3$ = 0.In any system of complex stress, to obtain a measure of the total amount of plastic straining suffered by any element of the material, it is necessary to add up all the increments of effective strain which the element has received, and the total effective strain may be written as

$$\bar{\in} = \int_0^{\bar{\in}} d\,\bar{\in} \tag{3.19}$$

For the particular class of loading paths in which all the stresses increase in the same ratio, proportional loading, i.e., the plastic strains are independent of the loading path and depend only on the final state of stress. There are two general categories of plastic stress-strain relationships. Incremental or flow theories relate the stresses to the plastic strain increments. Deformation or total strain theories relate the stresses to the total plastic strain. Deformation theory simplifies the solution of plasticity problems, but the plastic strains in general cannot be considered independent of loading path. Constitutive models or equations, stress-strain relations, and stress strain curves are analytical relations which express the linear or nonlinear relationships among stress, strain, strain rate, and temperature. Constitutive equations are dependent on specific characteristic of the material for certain processing conditions. In large plastic deformation, the von Mises yield criterion is usually used to provide data from uniaxial tension tests or compression tests to multiaxial deformation conditions. The coupling between the deformation analysis and the heat analysis of the work piece is given through the material constitutive relationship for the work piece. We combine the yield criterion, the stress-strain relations, and model the material to solve the deformations in a plastic deformation process utilizing proportional loading. The generally applicable yield criterion for plastic flow occurs according to the von Mises yield criterion plastic flow, given by the alternative forms of equation

$$\overline{\sigma} = f(\sigma) = \sqrt{\frac{1}{2}\left(\sigma_x - \sigma_y\right)^2 + \left(\sigma_y - \sigma_z\right)^2 + (\sigma_z - \sigma_x)^2 + 6\left({\tau^2}_{yz} + {\tau^2}_{zx} + {\tau^2}_{xy}\right)} = \sigma_y \quad (3.20a)$$

$$\overline{\sigma} = f(\sigma) = \sqrt{\frac{1}{2}(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 + \quad} = \sigma_y \quad (3.20b)$$

$$\overline{\sigma} = f(\sigma) = \sqrt{J} = \sqrt{{S_1}^2 + S^2 + {S_3}^2} = \frac{1}{2}\dot{s_{ij}} s_{ij} = \frac{{\sigma^2}_y}{3} \quad (3.20c)$$

and it says “yield occurs when the equivalent stress (Mises stress) equals the yield stress in uniaxial tension σ_y i.e. $\overline{\sigma} = \sigma_y$” [21,34,42].The relationships between stress and strain for an ideal plastic solid, where the elastic strains are negligible, are called flow rules or the Levy-Mises equations. The Levy-Mises equations can only be applied to problems of large plastic deformation because they neglect elastic strains. Plastic stress and strain relations were proposed by Saint-Venant who stated that the principal axes of strain increment are identical with the principal stress axes. The general three-dimensional equations relating the increments of the total strain to the stress deviations were given by Levy and independently by von Mises the equations given below are known as Levy-Mises equations and the equations can be given by the Levy-Mises which we can call constitutive flow rule (used for the rigid-plastic flow formulation) [24,78].

$$\dot{\varepsilon_{ij}} = \dot{\lambda}\frac{\partial \int (\sigma_{ij})}{\partial \sigma_{ij}} = \frac{3}{2}\frac{\dot{\bar{\varepsilon}}}{\bar{\sigma}} S_{ij} \quad (3.21a)$$

$$\dot{\lambda} = \frac{3}{2}\frac{\dot{\bar{\varepsilon}}}{\bar{\sigma}} \quad (3.21b)$$

$$\dot{\bar{\varepsilon}} = \sqrt{{}^{2}\!/_{3}\, \dot{\varepsilon_{ij}}\dot{\varepsilon_{ij}}} \quad (3.21c)$$

$$\bar{\sigma} = \sqrt{{}^{3}\!/_{2}\, S_{ij}S_{ij}} \quad 3.21d)$$

According to Levy-Mises equations, the total strain increments are assumed to be equal to the plastic strain increments, the elastic strain being neglected. Therefore, the above equations can only be applied to the problems of large plastic flow and cannot be implemented in the elastic-plastic range [63]. The Levy-Mises and Prandtl-Reuss equations provide relations between the increments of plastic strain and the stresses[61].The classical Prandtl-Reuss equations for isotropically hardening materials, as presented, e.g. are not restricted to small-strain, although it is necessary to specify for them a suitable materially objective stress rate when principal deformation axes are rotated[64]. The generalization of the equations to have both elastic and plastic strain due to Prandt and Reuss are known as the Prandtl-Reuss equations. Reuss assumed that the plastic strain increment is proportional to the instantaneous stress. Or by the Prandtl-Reuss flow rule (used for the elastic plastic solid formulation) [11,14, 34].

$$\dot{\varepsilon_{ij}}^{p} = \dot{\lambda}\frac{\partial f(\sigma_{ij})}{\partial \sigma_{ij}} = \dot{\lambda} S_{ij} \quad (3.21e)$$

$$\dot{\lambda} = \frac{1}{\tau_y}\sqrt{{}^{1}\!/_{2}\, \dot{\varepsilon_{ij}}\dot{\varepsilon_{ij}}} \quad (3.21f)$$

Finally we have the compatibility conditions given by the strain rate tensor [26,29, 34]

$$\dot{\varepsilon_{ij}} = \frac{1}{2}\left(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i}\right) \quad (3.22)$$

The unknowns for the solution of a plastic deformation process are six stress components and three velocity components. The governing equations are the three equilibrium equations, the yield condition, and five strain-rate ratios derived from the flow rule. The boundary conditions are prescribed in terms of velocity and traction. Along the roll-work piece interface, the velocity component is prescribed in the direction normal to the interface and the traction is specified by the frictional stress in the tangential direction. One possibility is to assume that Coulomb friction is present and that the interfacial shear stress equals the roll pressure P multiplied by a constant coefficient of friction μ

$$\boldsymbol{\tau} = \sigma_{fr=}\mu p \qquad (3.23)$$

Equations (4.1a-1b) through (4.21) are the governing equations of the mechanical problem and form the basis of the mathematical model for flat rolling.

3.2.6 Thermal Boundary Conditions

The thermal and mechanical problems are coupled through thermal strain loads and heat generation due to inelastic deformation and friction [65].Heat transfer plays a very important role in the rolling process. The thermal boundary value problem is described by the solution of the heat diffusion equation such that both transient and steady-state conditions satisfy thermal boundary conditions. Heat transfer phenomena are due to various sources. One source of heat is generated by friction on rolls-work piece contact regions and work piece plastic deformation, whilst heat loss sources are induced by radiation and convection to the environment from free surfaces conduction transfer to the rolls, and temperature changes during metallurgical transformations. Additional heat loss sources may be due to air or water cooling. All of these physical phenomena are a key part of our initial boundary value problem, which as we will see consists of a linear and homogeneous partial differential equation (heat equation), and a set of boundary and initial conditions. Thermal boundary conditions are assigned by setting mass density, thermal conductivity, and specific heat capacity. The plastic deformation is assumed to occur in the domain BCHG as shown in Figure 13**.**

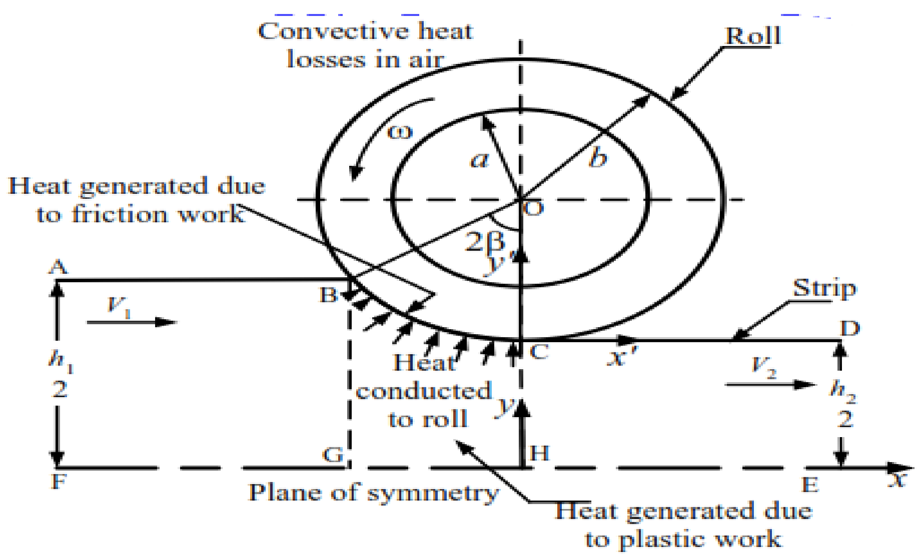


Figure3. 22: Schematic of upper half view and geometric arrangement of the heat generation for roll and bloom.

3.2.7 Thermal Balance Equations

Different researchers working in the field of metal forming for example using the hot rolling processes have classified the heat transfer [66] mechanisms and the various contributions to the overall heat balance for a particular cross section like bloom, billet, slab or strip can be summarized as: Heat loss to the environment by radiation and convection along the free surfaces, Heat gain arising from the work of friction forces on the contact surface, Heat gain arising from the work of plastic deformation, Heat loss by the conduction transfer to the roll, Temperature change due to the energy accumulated or realized during the metallurgical transformations [47]. According to the lagrangian coordinate, the energy equation in the cartesion system for the general heat conduction within the material is described by the general heat diffusion equation is as follows [19,32]

$$\frac{\partial}{\partial x}\left(k\,{}^{\partial T}\!/_{\partial x}\right) + \frac{\partial}{\partial y}\left(k\,{}^{\partial T}\!/_{\partial y}\right) + \frac{\partial}{\partial z}\left(k\,{}^{\partial T}\!/_{\partial z}\right) + \dot{q} = C_p \rho\,{}^{\partial T}\!/_{\partial t} \qquad (3.24)$$

The rate of heat generation takes into account the plastic work done, energy accumulated in the material due to the increase of dislocation density and heat produced during the softening process. The accumulated energy in the material is described by the equation given below [19].

$$\dot{q} = \int_v \left[\eta \bar{\sigma}_i \dot{\bar{\varepsilon}}_i^{\,P} - \upsilon A \dot{\bar{\mathcal{E}}}_i + \upsilon B \gamma e^{\left(-\frac{D}{KT}\right)}\right] dV \qquad (3.25)$$

The non-steady state temperature model, with a time-dependent term in equation (3.22), Should be applied to all cases of hot rolling of ingots, bloom and billets. During continuous rolling of rolling metal however, a steady state temperature field may be assumed in the roll gap and an additional term connected with heat convection due to the motion of the rolled metal needs to be introduced. A typical steady-state convective-diffusion equation is then written as[5,16, 39, 41, 60, 65]

$$\frac{\partial}{\partial x}\left(k\, {}^{\partial T}/_{\partial x}\right) + \frac{\partial}{\partial y}\left(k\, {}^{\partial T}/_{\partial y}\right) + \frac{\partial}{\partial z}\left(k\, {}^{\partial T}/_{\partial z}\right) + \dot{q} - C_p \rho\, {}^{\partial T}/_{\partial t} = 0 \quad (3.26)$$

To analysis the solution for the stress, strain, strain rate, velocity and temperature fields within the rolled bloom, appropriate boundary and initial conditions have to be introduced. Both steady-state and non-steady-state solutions have to satisfy the thermal boundary conditions, which may be of the following types [19]:The temperature is prescribed along the boundary surface

$$T(x, t) = T_s \quad (3.27)$$

The heat flux normal to the surface is prescribed along the boundary finite heat flux

$$k\, {}^{\partial T}/_{\partial n} = \ddot{q}_s \quad (3.28)$$

Adiabatic or insulated surface $\ {}^{\partial T}/_{\partial n} = o$ (3.29)

Convective heat transfer to the environment:

$$k\, {}^{\partial T}/_{\partial n} = h(T - T_\infty) \quad (3.30)$$

h = film convection coefficient , (T_∞) =environment temperature radiative heat transfer to the environment

$$\frac{\partial T}{\partial n} = \delta\varepsilon(T_w^4 - T_\infty^4) \quad (3.31)$$

Schematic illustration of the thermal events including the boundary conditions in the deformation zone is presented in Figure 14. As explained by Lenard [3,13]**,** main sources of heat losses include air cooling of the free surfaces and heat transfer to the cooler roll. In modeling, the axis of symmetry and the exit plane from the control volume are treated as insulated surfaces. Finally, constant temperature is prescribed along the vertical plane at the entry to the control volume. The temperature across the contact surface is allowed to be discontinuous, to account for the discontinuity created by the relative velocity between the two surfaces, and also that caused by the resistance to heat transfer across an interface. This latter effect can be specified as a function of the normal stress between the two surfaces in contact or by means of a constant heat transfer coefficient. Finally, interfacial frictional forces at the roll-bloom/slab interface and the shape of that interface need to be accounted for as well [15].

3.2.8 Heat Transfer from Mechanical Sources

As is well known one of the most important aspects in metal forming process is temperature. Temperature plays very important role in metal forming process and, in particular, in hot rolling process in terms of both rolling load requirements and the critical temperature of rolling the material. In the case, the temperature rise due to mechanical work or deformation is very significant. In this process the temperature rise is due to two factors: a) Friction derived mechanical work dissipated to the interface between the materials being rolled and the work rol**l.** b) Plastic deformation derived mechanical work absorbed by the material being rolled during deformation. This energy is not completely transformed into heat: as the deformation process progresses, the displacement of dislocations are being counteracted which causes internal stresses to appear at different points of the grains. The heat rate generated due to plastic deformation is determined by [11,14].

$$\dot{q} = \eta \overline{\sigma_{ij}}\, \dot{\bar{\varepsilon}}_{ij}^{\,P} \; \left({}^{W}/_{m^3} \right) \tag{3.32}$$

Where $\eta =$ heat generation efficiency (fraction of the plastic strain energy that is converted to heat ~ 0.9), $0 < \eta < 1$. $\overline{\sigma_{ij}} =$ Components of equivalent stress tensor (MPa) $\dot{\bar{\varepsilon}}_{ij}^{\,P} =$ Components of equivalent plastic strain rate tensor (s^{-1}).The heat transfer rate due to friction is expressed by [11,14].

$$q'' = \sigma_{fr}.v_r.M_{eq} \quad ({}^{W}/_{m^2}) \tag{3.33}$$

Where $\boldsymbol{\sigma_{fr}}$ =friction stress (MPa) , $v_r. =$ relative sliding velocity between the roll and the work piece (m/s), M_{eq} =fraction of friction energy that is converted to heat, 0< M_{eq} <1.

3.2.9 Heat Transfer Mechanisms:-

The most commonly heat transfer models that take into consideration in the hot rolling mechanisms are radiation and convection which heat transfer from the surface of the work piece to the atmosphere, in convection from the surface to cooling water, conduction both within the work piece and the rolls in the roll pass, as well as the adiabatic heating induced by the deformation of the roll pass (Figure:13 below).The complexity of the heat transfer mechanisms and their interactions, along with the difficulty of taking temperature measurements on an operating mill, have made the accurate quantification of the temperature changes in the rolling mil1is the subject of a substantial body of research.

3.3.1 Heat Transfer due to Conduction to the Rolls

The purpose of simulating heat transfer and heat generation is to model the effects of the temperature increase due to plastic work, to heat generated by electrical Joule heating and to temperature variation due to exchange of heat with the tools and the surrounding environment. The way we will model the heat flux at the heat roll interface is by using Fourier's law [67].

$$q^{"} = k(T_w - T_R) \tag{3.34}$$

Where $q^{"}$ = conduction heat flux ($W/_{m^2}$), k = conduction heat transfer coefficient ($W/_{m^2k}$), T_w= Work piece temperature (K), T_R = Roll temperature (K) K is not constant along the arc of contact and it is a function of: Roll pressure distribution, Interface oxide layer, Surface roughness, Surface chemistry (if lubricant used).

The conduction heat transfer coefficient in the contact area between the roll and the stock is very high and has values typically between 6000 and 10000$W/_{m^2k}$(8).

3.3.2 Convection Cooling Heat Transfer

Convection in the bloom hot rolling mill is due to the motion of air surrounding the work piece. Depending upon whether the air motion is forced or free, the heat transfer is referred to as either forced or free convection, the later being usually the case in hot rolling mills. A key factor in the calculation of temperature losses due to convection is to determine the heat transfer coefficient, which depends on the material temperature, ambient temperature, material specific heat and density, and the dynamic viscosity of the air flow and its characteristics, i.e., free, laminar, turbulent, etc.

In this thesis, the formula that will be used to study convection is the well-known Newton's law of cooling [32,33,50].

$$q^{"}conv = h(T_S - T_f) \tag{3.35}$$

$q^{"}conv =$ Convective heat flux (W/m^2), h = film convection heat transfer coefficient (W/m^2K)

T_S = work piece temperature (K), T_f = temperature of surrounding air or water (K)

In the hot rolling process we encounter two types of convection. The first one is the convection due to the air that surrounds the hot rolled metal. The thermal transfer coefficient h in this case is very low with values that range between $15^W/_{m^2k}$ and $50^W/_{m^2k}$.If we have force air convection, then the film coefficient becomes larger in the order of $500^W/_{m^2k}$.The second type of convection occurs in some hot rolling processes that use water in order to de-scale the work piece and also to cool the rolls that otherwise after several hours of continued rolling, begin to get too hot. The film coefficient in the case of water convection cooling reaches values ranging between 500 and $4000^W/_{m^2k}$.

3.3.3 Radiation Heat Transfer

Apart from the thermal flow due to convection, rolling stock heat is lost also due to radiation. The heat losses due to radiation can be determined from the Stefan-Boltzmann law [11,14, 33, 45, 54]

$$q^{"}rad = \delta\varepsilon\lfloor(T_w)^4 - (T_\infty)^4\rfloor \tag{3.36}$$

$q^{"}rad =$ Radiation heat flux (W/m),$\varepsilon = 8.0$emissivity of the work piece at a temperature around 1100℃, $\sigma =$Stefan-Boltzmann radiation constant of black body ,T_w= absolute temperature of the work piece, T_∞ =absolute ambient temperature ~ 20C+273 K = 293 K Since

$$q_{\ddot{rad}} = \frac{mC_\rho \Delta T_{rad}}{A_{rad}t} \tag{3.37}$$

Where m = mass of the rolled stock (kg), Cp = specific heat of stock (J/kg K), ΔT_{rad}= change in temperature (K), t = radiation time (s) A_{rad}= surface of radiating work piece (m^2) Therefore

$$\Delta T_{rad} = \frac{q_{\ddot{rad}}At}{mC_\rho} = \frac{\delta\varepsilon A_{rad}t}{mC_\rho}\lfloor(T_w)^4 - (T_\infty)^4\rfloor \tag{3.38}$$

This formula can be used to find the drop in temperature in the pass due to radiation. Finally, the heat generated by friction shear stresses τ_f in the contact interfaces with relative sliding v_r is given by $\dot{q}_{friction} = \tau_f | v_r |$

The transient heat diffusion equation (3.35/3.36), was firstly implemented by Kobayashi [67] in a finite element computer program for modeling thermo-mechanical metal forming processes, and subsequently implemented for modeling.

3.3.4 Surface Thermal Balance

Applying the energy balance for conservation of energy at the surface of the work piece,

$$S_{in} + S_g - S_{out} = S_{st} \tag{3.39}$$

Where $S_{in} = rate\ at\ which\ thermal\ energy\ enter\ through\ the\ control\ surface$

$\mathrm{S_g} = energy\ generation\ (thermal\ energy\ created\ within\ the\ control\ volume\ due\ to$

$conversion\ from\ other\ energy\ forms, in\ our\ case\ plastic\ deformation\ and\ friction)$

$S_{out} = rate\ at\ which\ thermal\ energy\ leave\ through\ the\ control\ surface,$

$S_{st} = rate\ of\ energy\ stored\ within\ the\ control\ volume.$

In Figure 14 five heat transfer terms are shown for the control surface. On a unit area basis they are the conduction within the work piece to its surface, and from the work piece to the rolls ($q^{"}cond$), the convection from the surface of the work piece to the surrounding, air or water ($q^{"}conv$), the net radiation exchange from the surface to the surroundings ($q^{"}rad$), and finally, the energy generation terms due to work of plastic deformation ($q^{"}_{pw}$), and friction ($q^{"}_{fr}$).

The energy balance then takes the form,

$$S^{"}_{st} = q^{"}_{pw} + q^{"}_{fr} \pm q^{"}conv - q^{"}rad \tag{3.40}$$

and we can express each of the terms using the appropriate rate equations,

$$S''_{st} = \eta\overline{\sigma_{ij}}\,.\,\dot{\bar{\varepsilon}}_{ij}^{\,P}\,l_{pw} + \sigma_{fr}.\,v_r.\,\text{ɡ} - K\,(T_w - T_R) - h\,(T_w - T_\infty) - \varepsilon\delta(T_w^4 - T_\infty^4) \qquad (3.41)$$

3.3.5 Constitutive relation, relevant for computer simulation of hot rolling of steels

Relations which characterize various responses (like mechanical, thermal, electrical etc.) of a material are called as the constitutive equations. Constitutive equation for such a response is usually expressed as a relation between the applied forces and the resulting deformation. Constitutive equations are formulations that can be fed into programs for processes such as rolling in order to achieve the desired product or for development of new products. Material behavior during such processes is often described with reference to processing variables such as strain, strain rate and temperature. A number of constitutive equations have been well studied and developed over a number of years and in steels of different compositions. These constitutive equations are often modified or used as a basis for development of new constitutive equations for describing a particular material under study. The hot rolling process is a thermo-mechanically coupled, where other than mechanical deformation under rolling there exists heat generation due to plastic deformation as well as frictional work and heat loss due to convection and radiation. The 3D part modeling the work rolls and work piece are carried in ABAQUS/CAE based on dimensional details mention[68].The constitutive behavior of the material in hot rolling processes above the recrystallization temperatures (700°C – 1200°C) depends on the type of material (low/high Carbon, alloys) strain rate, and working temperature [22]. In order to complete the finite element development for the finite deformation problem it is necessary to describe how the material behaves when subjected to deformation or deformation histories. Most of the empirical constitutive equations are based on the thermo dynamical concept that flow stress of a material depends on present values and past history of observable variables such as [69] strain, strain rate and temperature [70]. The equations relating stress, strain, stress rate (increase of stress per unit time), and strain rate are called the constitutive equations, since they depend upon the material properties of the medium under discussion. In the case of elastic solids, the constitutive equations take the form of generalized Hooke's law, which involves only stress and strain and is independent of the stress rate or strain rate. In plasticity however, the constitutive equations have a more difficult formulation, as they need to describe more complex phenomena. According to Lenard & Pietrzyk, functions describing the constitutive behavior of metals at high temperatures can be divided into several groups and The general relationship is of the following form[56]. Group I: functions $\sigma = \sigma T f(\mathcal{E}) A = \pi r^2 \mathcal{E}$ which account for the current strain, $(\mathcal{E})$ and, in some cases, for the initial stress (σ_y)or initial strain$(\mathcal{E}_0)$.Group II: functions, $\sigma = f(\mathcal{E}, \dot{\mathcal{E}}, T)$ which account for an influence of the current temperature (T), strain rate $(\dot{\mathcal{E}})$ and strain$(\mathcal{E})$. Group III**:** functions $\sigma = f(\mathcal{E}, \dot{\mathcal{E}}, T, \sigma_w)$which in addition to the temperature, strain, and strain rate, account for the influence of an internal state variable of the material(σ_w).Group IV**:** functions in which independent variables are the temperature, strain rate, strain and additionally time (t) and Group V: functions, which account for an influence of strain directions. The basic factors that affect the magnitude of yield stress are the temperature and the rate of deformation. Their influence in the hot working phenomena strain hardening and re-crystallization take place simultaneously. Therefore, the effects of strain hardening are not apparent. Assuming that the working temperature is constant, it can be concluded that the yield stress should also remain constant. The determination of the yield stress at temperatures above 700 ºC is a challenge. The stress-strain curve does not show any great change of direction on reaching the yield stress. Some researchers make the assumption that at these high working temperatures the yield stress differs very little from the ultimate tensile stress, and this value is sometimes defined as the constrained yield stress S=$2\tau_y = 1.15\sigma_y$. The temperature of the work piece has great influence on the strain rate. In order to study it, we will distinguish the following temperature ranges [56]. Hot working range: The strain rate has an important influence. The higher the strain rate, the higher the yield stresses. At very high temperatures, as the strain rate increases the heat has no time to be dissipated and remains in the metal, causing a rise in temperature. This result in lowering the temperature of fusion of the metal at high strain rates => the permissible temperature range for hot working becomes narrower. Therefore, low strain rates are necessary in hot rolling. The basic factor that decides the degree of plastic deformation of metal is the yield stress, which is dependent on the condition of the metal at the moment of deformation. Since the hot working deformation above the temperature of recrystallization processes the yield stress depends on: the kind of metal, the strain, the strain rate, and the temperature of working. Therefore functions in group II, III, IV, and V are the ones used to simulate hot forming processes. The determination of the right stress-strain equation to accurately model the flow stress of steel at high temperatures is an extremely difficult problem that is still not fully understood. The constitutive equation for the hot rolling problem is somewhat of a "holy grail" that every hot rolling company would like to discover. Many models that use group III functions $\sigma = f(\mathcal{E}, \dot{\mathcal{E}}, T, \sigma_w)$ have been proposed. We will focus on the Shida constitutive equation that is recognized as one of the most accurate ones in the existing reference. Shida's model for high temperature behavior of carbon steels. According to Pietrzyk and Lenard, the rigid-plastic flow formulation of the material based on the Levy-Mises model is more suitable for large nonlinear plastic deformations, as found in hot rolling processes. This plasticity law assumes that the effect of strain rate and temperature on material properties is much larger than the work hardening and the elastic deformations, in accordance with the incompressible flow hypothesis. Pietrzyk and Lenard reported that Shida in1969 developed empirical equations for low, medium, high carbon steels. These plasticity models describe the metal flow strength (σ) at high temperatures (T), as a function of strain rate, strain, and carbon content (%C), in austenitic,ferritic, and two-phase regions [35,53,54].The mathematical formulation of Shida's empirical relations is as follows[34,65]:

$$\sigma_p = \sigma_f f\left(\frac{\dot{\varepsilon}}{10}\right)^m (kg/mm^2) \tag{3.42}$$

Where for: $T \geq 0.95\frac{[C]+0.41}{[C]+0.32} \rightarrow \sigma_f = 0.28\exp\left(\frac{5}{T} - \frac{0.01}{[C]+0.05}\right)$ and

m= $(-0.019[C] + 0.126)\overline{T} + (0.075[C] - 0.05)$ While for: $T < 0.95\frac{[C]+0.41}{[C]+0.32}$ and

$$\sigma_f = 0.28q([C], T)exp\left[\frac{[C]+0.32}{[C]([C]+0.41} - \frac{0.01}{[C]+0.05}\right]$$ with

$$q([C]\overline{T}) = 30(C+0.9)\left[\overline{T} - 0.95\frac{[C]+0.49}{[C]+0.42}\right]^2 + \frac{C+0.06}{C+0.09}$$ and

m= $(0.081C-0.154)\overline{T} - 0.019C + 0.207\frac{0.027}{[C]+0.32}$ and

The remaining parameters in shida's equations are: $f = 1.3(5\varepsilon)^n - 1.5\varepsilon$, n=0.41-0.07C,

$\overline{T} = \frac{T+273}{1000}$. $\varepsilon\,\dot{}\,\varepsilon\; A = \pi r^2$. The symbol in the above equations does not have the physical meaning and used for the following ranges of parameters: T=temperature in℃, 700 ℃ $<$ T1200℃, C=carbon content in weight percent, C<1.2%, $\dot{\varepsilon}$= strain rate, 0.1< $\dot{\varepsilon}$ 100 s^{-1} , ε=true strain$<$ 70%. Shida's model was the constitutive model used in the hot rolling finite element method (FEM) simulation. All constitutive equations that are dependent on the temperature are part of what is known as temperature dependent plasticity. As seen in Figure 16, as the temperature increases, the stress-strain curve becomes more relaxed, i.e. the slope of the plastic part decreases [21].

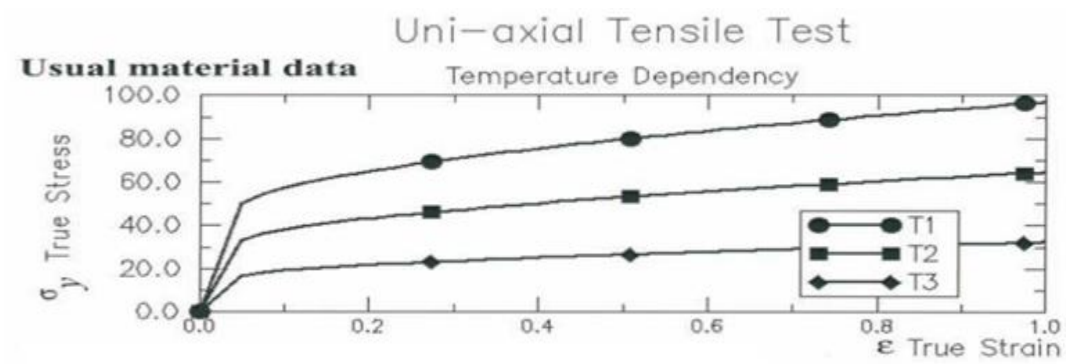


Figure3. 23: Temperature Dependent Stress-Strain Diagrams (T3>T2>T1).

The above behavior is perfectly captured by Shida's model for high temperature steel. The graphical representation of this equation is obtained by plotting the flow stress versus the strain, the strain rate and the temperature for the following ranges for each of the three independent variables: $0 \leq \varepsilon \leq 1$, $1 \leq \dot{\varepsilon} \leq 5\dot{0}(S^{-1})$, $700℃ \leq T \leq 1200℃$.The following plots show the Shida flow stress surfaces for strain rates of 1, 5 and 10S^{-1}.For each strain rate we obtain a different Shida flow stress surface, and within that particular surface, for every value of strain and temperature we obtain a value of flow stress. Therefore, within the ranges for each of the three independent variables, each set of three values uniquely determines a value of the flow stress. This model is particularly convenient for the hot rolling process where as the work piece deforms, the strain, strain rate, and temperature all change simultaneously. Modeling has two main objectives: prediction of metal deformation and loads required producing that deformation, but it can also help in predicting causes of failure. Industrial practice usually depends on production of a required change without having undesirable stresses and strains in the final material. Therefore, material modeling is very significant for mathematical modeling of metal forming processes. The behavior of the material under processing conditions must be taken into consideration in the analysis, design, and control of metal forming processes. The material modeling involves several aspects which directly and indirectly affect the deformation process. Direct factors which affect the deformation process are: the temperature of the deformation process and strain, and strain rate while the indirect factors are: metallurgical structure and Grain size, transformations of phase, and strain history. The constitutive modeling provides the relationship between stress and strain and between the strain rate and temperature. This relationship is used in the analysis and prediction of the following: (1) Metal flow which contains velocities and strains (2) Temperatures (3) Flow stress and stresses. In constitutive modeling, the flow stress is expressed as a function of other process parameters, such as strain and temperature, which describe the state of the plastic deformation in the deforming metal. The effect of deformation parameters on plastic flow and fracture can be expressed in terms of the flow-stress behavior[22].

3.3.6 Numerical (Mathematical) Models for Rolling Force

Based on thermo-mechanical coupled FEM, a mathematical model has been developed to predict flow stress, rolling force, contact normal force and friction force during hot continuous rolling process [26].Hot rolling theory allows roll force to be evaluated. Theory has not yet advanced enough o give accurate answers to all problems and quantitative terms. Early publications in hot rolling theory tended to be application specific. Hence, some research results are not widely applied in industry. The resistance to deformation of material depends upon its chemical composition, rolling temperature, and conditions of deformation. Till now none of the formulae provided a method for calculation of resistance to deformation with perfect accuracy, since certain simplifications and hypothesis have been used in each case. Therefore, the most acceptable research method is based on experimental investigations. Numerous mathematical models have been developed for prediction of rolling force in hot rolling operations ranging from very simple to very complex expressions. The outline important mathematical modeling approaches and a significant part of the theory can be briefly introduced in a literature review of chapter two. In the hot rolling process of a bloom is studied by using the rigid-plastic finite element method. The 2D models of the roll and the bloom are developed to investigate the effect of different process parameters such as initial rolling temperature, bloom thickness, rolling speed, friction coefficient, and reduction rate on the rolling force, normal force, and effective stress distribution. Moreover, friction distribution in the deformation zone is also studied based on 3D models [71].One of the important applications of constitutive equations in hot rolling is the roll-force calculation, which requires other parameters, such as roll diameter during rolling, thickness of slab at roll entry and roll exit, and the friction between the work piece and the rolls. One of the commonly used models for roll-force calculations is the Sims method that explained in the chapter two, which simplified the slab analysis and assumed that only sticking friction exists in the roll contact zone [69].

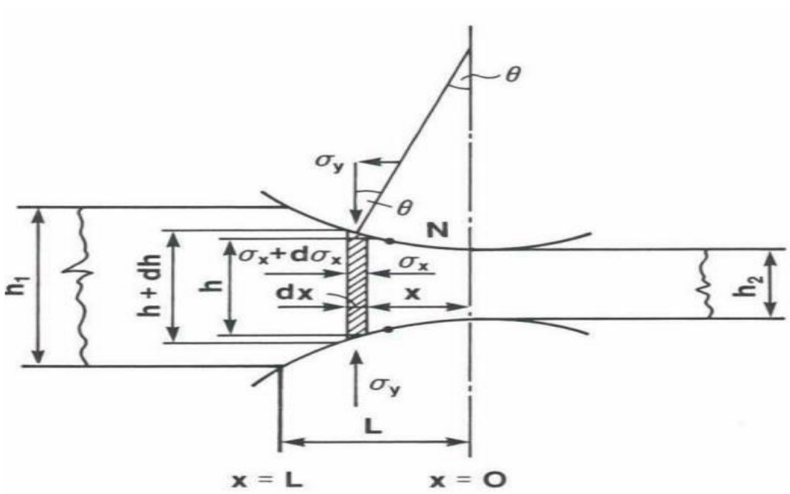
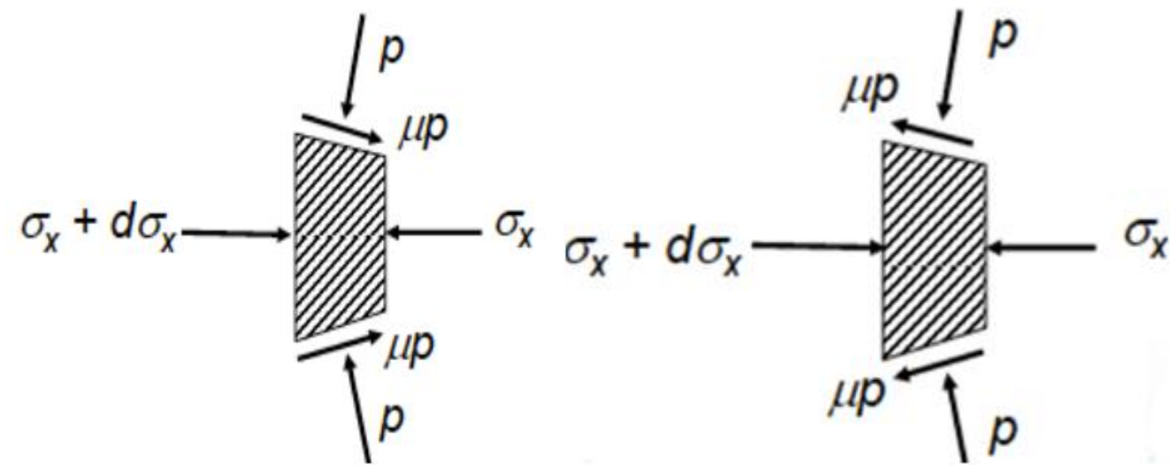


Figure3. 24 : Schematic Representation of the deformation zone in flat rolling.

Rolling cannot take place without friction, for rolling to occur $\mu > \tan(\alpha)$



Stresses in the slab on the entry-zone Stresses in the slab on the exit-zone

The horizontal forces acting on vertical faces of the section dx produce compressive stresses $\sigma_x + d\sigma_x$ acting on the face of the section of height $h + dh$ and compressive stresses σ_x acting on the face of height h.The equilibrium of the horizontal forces acting on section dx [36] may be expressed as

$$(\sigma_x + d\sigma_x)(h + dh) \pm 2\mu\sigma_y \cos\theta \frac{dx}{\cos\theta} - 2\sigma_y \sin\theta \frac{dx}{\cos\theta} - \sigma_x h = 0 \quad (3.43a)$$

$$(\sigma_x + d\sigma_x)(h + dh) - \sigma_x h - 2PRd\theta sin\theta \pm 2\mu PRd\theta cos\theta = 0 \quad (3.43b)$$

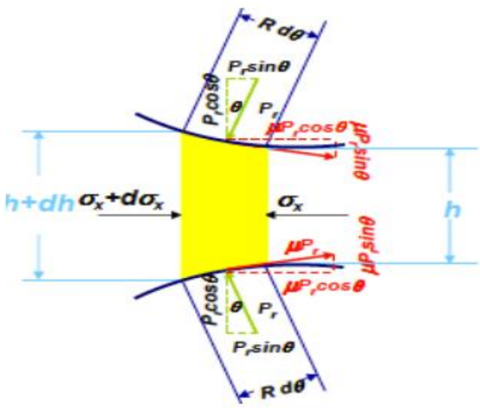
$$(\sigma_x + d\sigma_x)(h + dh) \pm 2\mu\sigma_y dx - 2\sigma_y tan\theta dx - \sigma_x h = 0 \quad (3.43c)$$

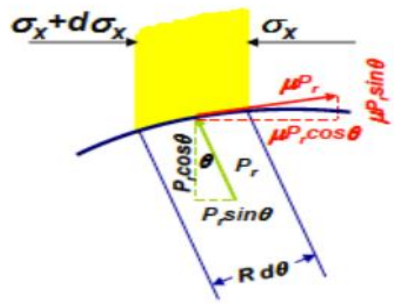
Simplifying and ignoring higher order terms restricting the analysis for contact angles < 6 degrees α <1then sin φ= φ and cos φ) =1

Or $2\sigma_y(tan\theta \ \mp \mu)dx = d(h\sigma_x)$ (3.44a)

Or $\frac{\delta(\sigma_x h)}{d\varphi} = 2PR.(\sin\varphi \mp \mu\cos\varphi)$ (3.44b)

The angle φ designates any point of contact between the material and the roll surface. The stresses present are the radial pressure p and the tangential stress generated by friction μp.The stress σ_x is assumed to be uniformly distributed in the secton.





$dx = Rd\theta sin\theta = Rd\theta sin\emptyset = Rd\theta cos\theta$,where the (-) sign before μ corresponds to the sections dx located between the entry and neutral planes and sign (+) corresponds to the sections dx located between the neutral and exit planes. For Plane Strain conditions and using the Von Mises criterion

Since $tan\theta = \frac{1}{2}\frac{dh}{dx}$, equation (2.25) can be rewritten as

$$\sigma_y \frac{dh}{dx} \mp 2\,\mu\sigma_y = \frac{d(h\sigma_x)}{dx} \qquad (3.45)$$

Taking into account the yield criterion given by Equation (4.56) for the case of plain strain,

$\sigma_y - \sigma_x = 2\tau_y$ and that $p = \sigma_y$ we obtain the differential Equation (4.57) in its final form

$$p\frac{dh}{dx} \mp 2\,\mu p = \frac{d[h(p-2\tau_y)]}{dx} \qquad (3.46)$$

Equation (4.58) was derived by Von Karman in 1925 and is the starting point in the analysis known as the theory of homogeneous deformation [19]. A number of solutions to this equation have been proposed.

According to Ginzburg, Von Karman's solution is based on the assumption that dry slipping would occur over the whole arc of the contact between the rolls and the rolled material. Also the frictional shear stress is directly proportional to the value of local normal pressure, i.e.

$$\tau = \sigma_{fr} = \mu\sigma_y = \mu p \qquad (3.47)$$

Ekelund's solution is based on the assumption that the dry slipping would occur over the whole entry side, and sticking over the whole exit side of the arc of contact Siebel's solution is obtained for the case when the dry slipping occurs over the whole arc of contact between the rolls and the rolled material and it is assumed that the frictional force is constant along the arc of contact ($f_{fr} = constant$) Nadia's solution is based on the assumption that viscous slipping exists in the roll contact zones and that the frictional force is proportional to the relative velocity of the slip. Thus,

$$\tau_x = \mu \frac{(V_x - V_r)}{\delta} \quad (3.48)$$

Where V_x =velocity of the metal being rolled at the section dx (Figure 2.5),V_r =Peripheral roll velocity,δ = oil-film thickness.

Analysis of bloom rolling must be able to provide the pressure distribution in the roll gap, the roll force and torque with accuracy and consistency. Several analyses have been published in the literature. The theory of homogeneous deformation suggested by yon Karman was based on simplified equilibrium of forces acting on a slab element in the deformation zone of strip. Orowan discarded the assumption of homogeneous deformation and developed a theory of Inhomogeneous deformation. The differential equation for bloom element was derived under various assumptions and approximations by Nadai, Bland and Ford and Sims, Orowan and Pascoe's solution is derived for the case when sticking occurs over the whole arc of the contact.

CHAPTER FOUR

Finite Element Method Modeling in Metal Forming

Finite Element the Method (FEM) is one of most widely used numerical methods in the world of engineering because it is a powerful numerical technique to solve the partial differential equations that govern physical problems. FEM is widely applied to start from stress and deformation analysis in the fields of automotive, fluid flow ,building structures, bridges and aviation is analysis, heat transfer, magnetic fields, and other non-structural problems [17].As it is observed there is a complex interconnection between governing equations. In order to solve these equations, the simulation was carried out (conducted) by a 3D coupled thermo-mechanical FE analysis using commercial FE software package ABAQUS/Explicit [72]. Combining the merits of both Lagrangian and Eulerian formulations, ALE formulation was developed to handle mesh distortion, mesh entanglement, and special boundary condition changes in hot rolling process [73]. Since in metal forming operations, elastic strains contribution is negligible with respect to nonlinear plastic strains, a rigid-plastic approach can be reasonably adopted for the analysis [22]. According to the work of [56] and [74], thermal and mechanical problems need to be solved simultaneously. The coupling occurs when large plastic deformations and contact pressure generate heat transfer which is a source of changes in the mechanical problem. Updated lagrangian formulation through the use of the software is selected to solve the coupled thermo-mechanical problem according to Pietrzyk and Lenard [45]. The temperature distribution and velocity field, strain rate, strain and stress fields are calculated in the deformed zone. A full 3D model of 950 mm diameter work roll and bloom of dimensions (320×320×3000) mm has been developed to simulate single-pass hot rolling processes. Due to the rapid development of computer technology, finite element analysis acquired a wide application in the field of hot rolling and the accuracy of the results depends on the quality of assumptions made. Computer simulation of the rolling processes is an important alternative to complement or to replace the expensive experimental procedures associated with innovative development [75]. In the last many years, with the development of computing, more sophisticated simulation models have become possible. A significant contribution has been made in the area of computer simulation of rolling processes. The flow theory of plasticity, with rigid-plastic material models has been found to be quite suitable for the mechanical description of hot rolling processes. Application of the theory of plasticity requires a geometric definition of the problem with the appropriate boundary conditions. Analysis must uniquely satisfy equilibrium, compatibility and material behavior relations. Analytically this is generally difficult, and usually impossible, so apart from simple problems, solutions are generally numerical. Finite element method has made it possible to obtain accurate approximate the numerical solutions. A finite element method has emerged as a powerful and useful computational tool for a variety of purposes. It is fair to say that nowadays for most complex problems, where exact analytical solutions are not available, FEM offer a reliable route to arrive at accurate solutions for boundary value problems involving large-deformations and material non-linearity[76] . A nonlinear 3D FE model was developed to study hot rolling of a square mild steel bloom. The steel bar was built as a three-dimensional deformable part using 8-node brick element (C3D8RT), and rollers were modeled as rigid parts using 4-node rigid element (R3D4) .The first stand of the full hot rolling process was modeled and simulated. The FEM is now probably the most common technique used to investigate rolling problems. In this chapter, the principle of FEM is described and this is followed by a description of its applications to hot rolling.

4.1 Procedures and Principles of Finite Element Analysis in Metal Forming

Applying the FE method to aid predictions on the metal forming industry has been an international research focus during the last decade. This could be proved from the proceedings of any of the recent conferences on metal forming. The reason can be attributed to the characteristics of the metal forming processes: large deformation, thermo-mechanical coupled, non-linear boundary conditions and non-linear material behavior. The FEM used in metal forming can be generally categorized into rigid-plastic FEM, elastic-plastic FEM and plastic FEM, in terms of the type of material constitutive model employed (Hartley 1993).For some hot processes, such as forging, rolling and extrusion, plastic strains outweigh elastic strains; the material is regarded as a non-newton fluid, and rigid-plastic FEM is usually adopted to simulate these processes [77].Most of the physical systems can be modeled by partial differential equations. The state variable in the system is assumed as a continuous function. A geometrically complex domain of the problem is divided into finite number of sub-domains called finite elements. The elements are interconnected by the common nodal points. An approximate interpolation function (or shape function) is chosen for the field variable in the elements. In the case of variational approach, proper functional is formulated depending upon the specific constitutive relations. The functional is expressed locally within each element in terms of the nodal point values. When the condition for this functional to be stationary is applied, it results in the stiffness equations. These stiffness equations are then solved using appropriate boundary conditions. The application of the finite element method to the metal forming problems began as an extension structural analysis techniques to the plastic deformation regime. Thus, early applications of the finite element method to the metal forming problems were based on the plastic stress-strain matrix developed from the prandtl-Ruses equation. An analysis method in the area of metal-forming application in many cases can be justified only by its solution reliability computational efficiency. This realization has led to the development of numerical procedures based on the flow formulations. The following sections give a briefly introduction to FEM. Procedures and principles of FEA [56]. According to Mottram (1996): the year 1956 can be considered as the birth of the finite element method; the name was first used by Clough who saw a model as consisting of a finite number of elements (or sub regions).The first FEM formulations for forming processes took place in 1974 and were based on the so-called flow formulation, which considers the material to be a Newtonian viscous fluid. The basis of the finite element Method is the representation of a body or a structure by an assemblage of subdivisions called finite elements, which are often referred to as a mesh (Fenner 1996). These elements are considered to interconnect at joints, which are called nodes or nodal points. The domain is then an assemblage of elements connected together appropriately on their boundaries. For a two dimensional continuum the finite elements may be triangles, a group of triangles, or quadrilaterals. For 3D analyses, the FE may be in the shape of a tetrahedron, rectangular prisms, or hexahedra. The path to the solution of a problem formulated in a finite element problem consists of the following processes (Kobayashi 1983): (a) identification of the problem; (b) definition of the element; (c) establishment of the element equation; (d) the assembly of element equations; and (e) the numerical solution of the global equations.

The properties of the finite element method .The main advantages of the finite element method are: The capability of obtaining detailed solutions of the mechanics in a deforming body, namely, to determine velocities, shapes, strains stresses, temperatures, or contact pressure distributions. A computer code can be used for a large variety of problems by simply changing the input data. However, a large number of nodes are needed to model plastic flow in addition to a very large number of iterations needed to achieve a solution. Thus, significant computing capacity is required. Comparison is both iterative and slow. Most published finite element work on metal rolling still uses some approximation in order to reduce the problem size and hence reduce computation requirements. Finite element methods techniques will undoubtedly become more popular as the price of computing comes down and speed and memory increases. In the past few years FEM has been extensively used for metal rolling analysis and now it is probably the most common technique employed to investigate rolling problems [56].In this chapter, the principle of finite element method is described and this is followed by a description of its applications to hot rolling and give a briefly introduction to FE method.

4.2 The Properties of the Finite Element Method

The main advantages of the finite element method are: The capability of obtaining detailed solutions of the mechanics in a deforming body, namely, to determine velocities, shapes, strains stresses, temperatures, or contact pressure distributions. A computer code can be used for a large variety of problems by simply changing the input data. However, a large number of nodes are needed to model plastic flow in addition to a very large number of iterations needed to achieve a solution. Thus, significant computing capacity is required. Comparison is both iterative and slow. Most published FE work on metal rolling still uses some approximation in order to reduce the problem size and hence reduce computation requirements. FEM techniques will undoubtedly become more popular as the price of computing comes down and speed and memory increases. In the past few years FEM has been extensively used for metal rolling analysis and now it is probably the most common technique employed to investigate rolling problems (Edwards 1990, Hartley 1989 and Kobayashi 1985).

4.3 Finite Element model ABAQUS Software

In recent years, there has been substantial academic and commercial interest in making Finite Element analysis more accessible to non-specialist user. A typical input file in ABAQUS is consisted of two main sections: Model definition and history definition. The following listing is a typical input file used in this investigation to simulate the bloom rolling process. In the model definition section the geometry and material properties are described. The geometric definition consists of giving the coordinates of the nodes, and describing the elements that make up the model. The material property description consists of the elastic material properties, effective stress-effective, plastic strain response for nonlinear analysis, and the friction conditions for contacting surfaces. The history definition consists of prescribing the variation of external parameters to which the response of the system is needed, and specifying the desired output. In this section the loading definition, prescribed boundary conditions, and special output options are defined [78].The hot rolling process is simulated with a 2D (plane strain) ABAQUS/Explicit thermo-mechanically coupled model using rigid work rolls. The input file for a single pass is automatically created applying a python script using all necessary geometry data like bloom thickness, reduction per pass, roll diameter, velocity of the roll stock collected from the process database of the hot rolling mill. Optimized meshing parameters are chosen also automatically within given boundaries (e.g. number of elements through thickness as well as along the contact zone, maximum aspect ratio) [53].A complete ABAQUS analysis usually consists of three distinct stages linked together by files as shown in Fig. below.

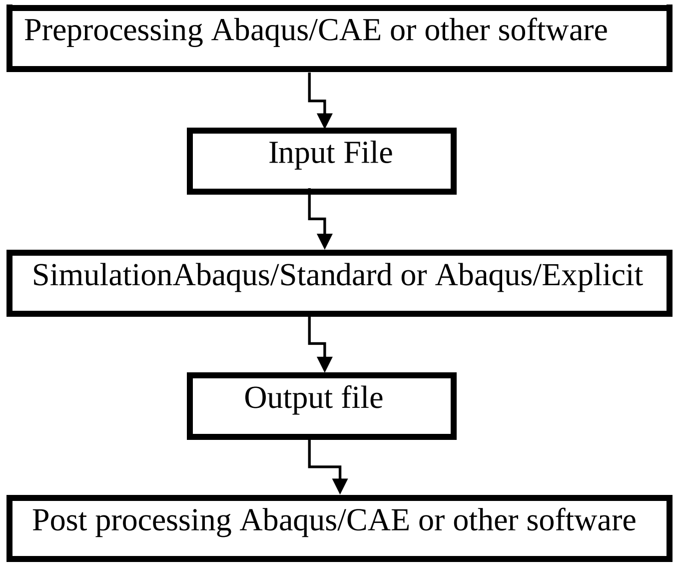


Figure4. 1: Stages of ABAQUS analysis

4.4 Simulation Methodology

The simulation of many physical problems requires the ability to model the contact phenomena. This includes analysis of interference and manufacturing processes among others.

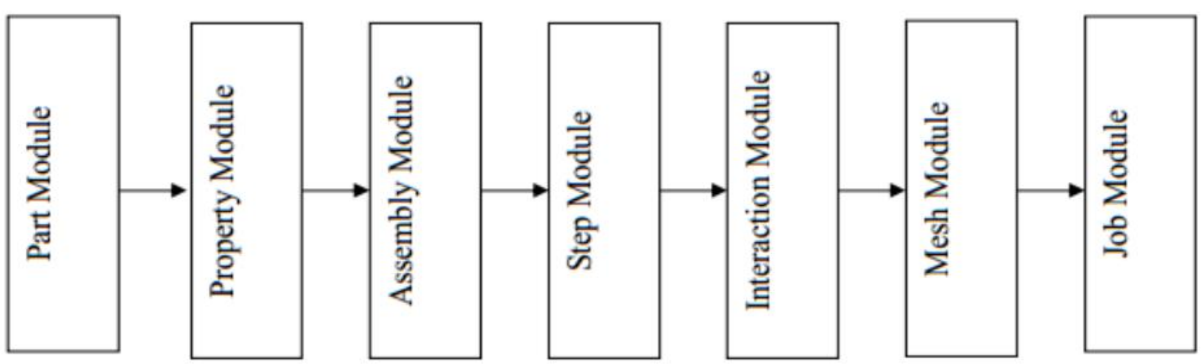


Figure4. 2 :Rolling methodology of abaqus analysis.

The analysis of contact behavior is complex because of the requirement to accurately track the motion of geometric bodies, and the motion due to the interaction of these bodies after contact occurs. This includes representing the friction between surfaces and heat transfer between the bodies if required. The numerical objective is to detect the motion of the bodies, apply a constraint to avoid penetration, and apply appropriate boundary conditions to simulate the frictional behavior and heat transfer [79].The term simulation is derived from the Latin word "simulare" what means "to pretend". However, the technical meaning of simulation is the description and reproduction of physical and technical processes by use of mathematical and physical models. In comparison with practical tests, the simulation often is cheaper and not so dangerous. Combined with modern methods of computation, the simulation is a powerful tool which gains more and more importance for describing and developing new processing methods. Numerous finite element programmes have been developed which are able to solve linear, non linear, static, dynamic, elastic, plastic, elastic plastic, steady state, transient, isothermal as well as non isothermal problems [80].There are currently no commercial codes in the marketplace that specialize on rolling simulations. ABAQUS and MSC. Marc have been used extensively to analyze the rolling process whereas ADINA, ANYSY, DEFORM-3D, FORGE3D, LS-DYNA and MSC. Super Forge (finite volume) is mainly used for sheet metal forming and forging applications. Each commercial code has its speciality.For rolling, the capabilities of autom(atic meshing and remeshing, thermo mechanical coupling and easy transfer of deformation history from one pass to another pass are crucial [77]. Current software includes finite element components developed in-house and other commercial finite element codes used alongside ABAQUS. The software simulates the temperature evolution of a rolled material through a rolling mill and predicts the microstructure and thermo-mechanical properties of the rolled stock. [70]a coupled thermo-mechanical simulation model was developed using the commercial finite element code ABAQUS/Explicit version 6.14. The rolling model is three-dimensional, thermo-mechanical, transient and nonlinear. General Software Packages Analysis includes three stages. Finite element methods (FEM) software can meet most of the needs in industry. The commercial finite element software ABAQUS is used to solve the rolling mill simulation problem where output is determined in terms of general mechanical variables that include displacement, strain, stress energy, etc. The finite element model currently used in this work is based on lagrangian and transient arbitrary eulerian-lagrangian (ALE) formulations.[70] In application finite element programs use of the following processes:

4.5 Pre processor (user) Build a finite element model

Preprocessing is the initial phase of the Finite element analysis program. This phase includes all of the tasks that take place before the numerical solution process. This usually assists the analyst in carrying out the following operations:(a) Definition of geometry in computation form; (b) Definition of a mesh of nodes and elements to represent the geometry; (c) Definition of appropriate Section of boundaries of the geometry, in terms of the mesh data, at which boundary conditions will be applied; (d) Definition of the boundary conditions; (e) Definition of material and physical properties for groups of elements; (f) Application of control parameters for the solver. The pre-processing programs tend to have a user-friendly interface. It allows various parameters to be set and resulting changes to be seen quickly. This is of particular importance when the geometry of the design is being created and when the mesh is being built. However, this is not an easy task and several approaches have been proposed. ABAQUS/CAE is divided into modules, where each module defines an aspect of the modeling process; for example, defining the geometry, defining material properties, and generating a mesh. As you move from module to module, each module contributes keywords, parameters, and data to form an input file that you submit to the ABAQUS/Standard or ABAQUS/Explicit solver for analysis. For example, you use the Property module to define material and section properties and the Step module to choose an analysis procedure; the ABAQUS/CAE postprocessor is called the visualization module.

4.6 Modeling and Analysis

The analysis of the horizontal rolling processes makes use of the finite element method based on the flow formulation for slightly compressible rolling materials. In the case of thermo-mechanical analysis of rolling processes, it is considered that the heat generation rate in the deforming work piece is due only to plastic deformation. The mathematical modeling of the problem in the present work is composed of analyses the steady-state thermo-mechanical behavior of the bloom was formulated in the deformation zone and the stress distribution as well as the temperature rise on the bloom–roll interface area was used as boundary conditions for solving the thermo-mechanical equations. hot rolling is a multi-pass process where the initial square or rectangular cross-section geometry of a bloom is transformed into the desired shape by means of a sequential forming performed by successive passes between pairs of shaped rolls .Using finite element software package created 3D rolling model and simulate a one move of the hot rolling process for mild steel bloom. Mesh definition is the process of converting a physical problem into discrete geometric entities for the purpose of analysis. The mesh generation procedure required of all FEM simulations remained a time-consuming operation. In conventional mesh generation procedure, FEM users are required to decide which mesh density will achieve the best solution with minimum use of central processing unit time. The quality of the FEM mesh depends on the user's experience and actual mesh construction is time consuming. Results from meshing simulations in Abaqus show a gradual improvement in the FEM results. Before a body can undergo finite element analysis, it must be modeled into discrete physical elements. Mesh generation is one of the most critical aspects of engineering simulation. The meshing of the model of the Mild steel bloom was done with C3D8R elements with hourglass control of ABAQUS 6.14 finite element tool, which due to its shape, is also known as 8 node brick element. As this analysis was expected to have very large deformations, the adaptive meshing capability available in ABAQUS/Explicit was used with a frequency of [40] and [30] mesh sweeps per increment. The adaptive mesh control manager of ABAQUS reduces the amount of mesh distortion and maintains a high quality mesh throughout the analysis. The mesh influences the accuracy, convergence and speed of the analysis. Structural mechanics simulations need to use the mesh efficiently as run times can be impaired with high element counts. ABAQUS Meshing has a physics preference setting ensuring the right mesh for each simulation. After the proper model is finished, the computational mesh that is used as a basis of solution procedure should be generated. The mesh consists of discrete elements located throughout the computational domain. A good computational mesh is an essential ingredient for a successful and accurate solution. If the overall mesh is too coarse, the resulting solution may be inaccurate. To achieve the required precision in the simulations an adequately fine mesh is required, which must be carried out due to the three-dimensional stress state with continuous elements (full 3D elements). Due to the large plastic deformations the simulation mesh requires continuous remeshing to prevent the simulation from failing due to extremely distorted elements. If the overall mesh is too fine, the computational cost may become prohibitive. So the mesh was fine near the contact and course away from the contact surfaces as it is seen in Figure below.

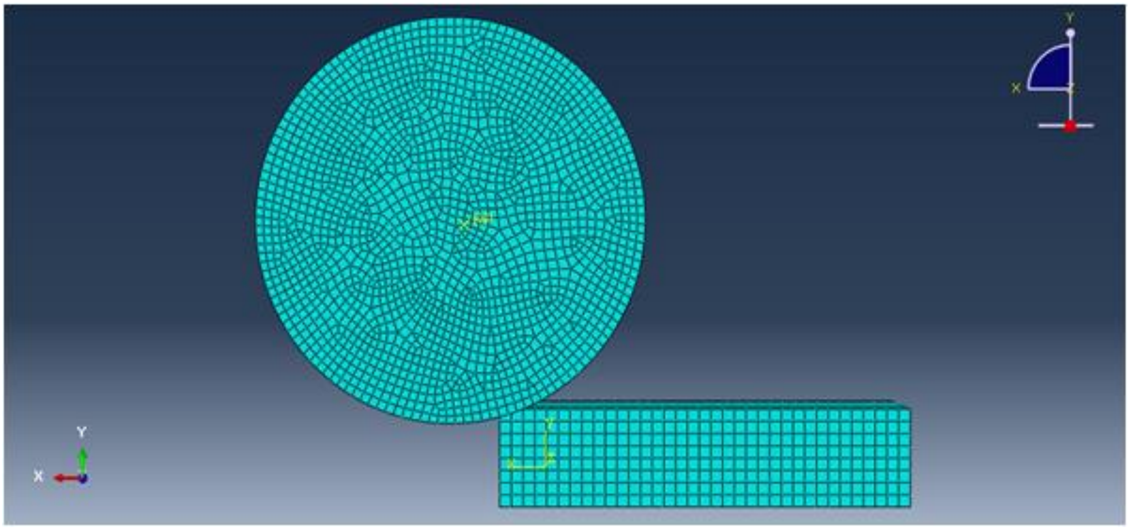


Figure4. 3: Assembled components of bloom and roller model of meshed components in finite element (mesh generation).

Mesh encompasses the placement of geometric coordinates and the grouping of nodes into elements. A valid mesh definition, the nodes must have geometric coordinates and must be connected to an element. First, describe the element by entering the element number, the element type, and the node numbers that make up the element. In general meshes created by first applying a global seed size. A lower global seed size corresponds to a finer mesh. To make the bloom have more elements with respect to the bloom thickness, the mesh layers were added. The mesh thickness represents the number of mesh layers along the thickness. Higher mesh thickness means the bloom thickness was divided into more layers of elements. The finite element mesh used in this simulation for a full model of the bloom is shown in Fig 20 The type of element is brick element with total number of element of 4536 and total number of nodes of 5698 nodes.

A 3D hexahedral element was employed to mesh the complicated geometry of the bloom (especially when deformated). A mesh refinement analysis was performed for the first pass and the analysis showed that a 30-40 mm mesh element size was adequate. The model is able to regenerate the mesh to replace the excessively distorted elements during the simulation of the rolling process. The rolls were considered as rigid bodies for the simulations. In the present work, the rolling mill configuration and the billet were modeled using ABAQUA software and then exported to the FEM software.

Type of rolling	Hot rolling
Type of simulation	3d without flash
Type of analysis	Flow analysis
Deformation	Rigid plastic
Bloom material	ASTM/A36 mild steel
Friction	0.3
Material temperature	1000°C-1300°C
Mesh Size	30-40

Table3. 6 :Rolling parameters used for simulation hot rolling processes.

4.7 Simulation stage or Solvers (Computer) Conduct numerical analysis

The actual finite element analysis is carried out in this section. The basic equations of equilibrium, constitutive relations and boundary conditions are translated into nonlinear algebraic equations by utilizing the FEM discretization procedure. The user does not have access to this module. He can select one of the two available solution techniques for solving simultaneous equations namely direct iteration method or the Newton-Raphson method. All the input data and output data are stored in binary form, which are accessed by the user through the post processor. The results of each calculated step are stored and then can be displayed or plotted through the post processor too. Usually this program both sets up the required numerical equations that describe the behavior of a structure under a given set of boundary conditions and also solves the equations. The solver reads all the relevant data that has been defined by the pre-processor, usually held in files written by the pre-processor, then carries out the necessary numerical operations and writes the results to further files. A further function of the solver is data checking. The solver checks to see if the data that is read is acceptable before attempting to produce a solution. The rotation of rolls causes bloom to go through roll gap and obtain desired thickness. To happen this various inputs are given before starting the simulation. The table shows simulation process input parameters. Once the simulation starts the material is auto meshed into tetrahedral meshing as shown in figure.

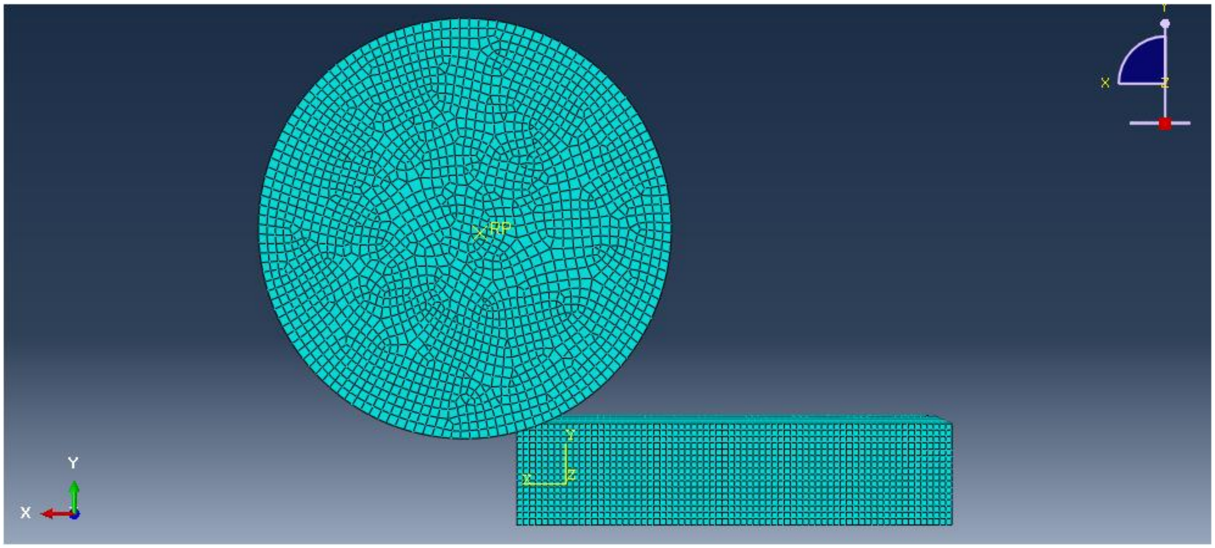


Figure4. 4: tetrahedral meshed work piece in abaqus software.

4.8 Post-processors (user) See Results

Post processing stage is the stage where results generated in the analysis are visualized once the simulation completed**.** In terms of post-processing, efforts have been focused on establishing graphical facilities for displaying the results coming out of the numerical simulation. As the solver generates large amounts of information; graphical interpretation is often the only means of assessing the results. Hence, the post-processor is devoted to the display of the results, giving a picture of the results and making extensive use of color with the proliferation of computers and software, many people have been used to buying a package and getting results. Unfortunately, any software that solves partial differential equations will not, by its very nature, be as mature as other simpler engineering analysis tools that are also on the market. ABAQUS has been used to simulate hot rolling in wide range applications. These bring out the manner in which the relevant physical quantities are calculated by ABAQUS. ABAQUS generally uses Newton's Method as a numerical technique for solving non-linear equilibrium equations. It is available in both explicit and implicit formulations. The potential of attaching user defined subroutines make ABAQUS a powerful tool to model problem-specific areas such as contact friction and interface heat transfer, which are vital in modeling the evolution of microstructure. However, the availability of user-defined subroutines is limited for the explicit formulation. ABAQUS is commercial FE software that used to solve the rolling mill simulation problem where output is determined in terms of general mechanical variables that include displacement, strain, stress energy, etc.

4.9 Thermal Mechanical Finite Element Modeling in Rolling

The simulation of metal forming Processes by using of the FE method was originated in the late of 1960's and Fast development of finite-element simulations of metal forming processes has been observed since then [81]. This development has been parallel to the development of supercomputers. With today's supercomputers, the application of the FEM to the simulation of manufacturing processes is becoming more and more popular. Modeling and simulation of manufacturing processes are tools to better understand and thereby solve new problems arising during the transformation raw material to the new materials and geometries[56].Finite element analyses of non-linear problems such as those found in metal deformation are common nowadays. The FE method allows the solution of complex initial boundary value problems by combining the best of numerical methods and supercomputing, which allows the fast solution of the millions of equations that are generated by a finite element model. As explained in [56] the basic concept of the FE method is one of discretization.The FE model is constructed in the following manner. A number of finite points are identified in the domain of the function, and the values of the function and its derivatives, when appropriate, are specified at these points. The points are called nodal points. The domain of the function is represented approximately by a finite collection of sub domains called finite elements. The domain is then an assemblage of elements connected together appropriately on their boundaries. The function is approximated locally within each element by continuous functions that are uniquely described in terms of the nodal-point values associated with the particular element [19].The path to the solution of a finite element problem consists of five specific steps: a) Identification of the problem, b)Definition of the element, c) Establishment of the element equation, d) Assemblage of the element equations, e) Numerical solution of the global equations. The formation of element equations is accomplished by one of four approaches[56]: (a) Direct approach, (b)Variational methods, (c) Method of weighted residuals, (d) Energy balance approach. The basis of finite element metal flow modeling, for example, using the variational approach, is to formulate proper functional, depending upon specific constitutive equations. The solution of the initial boundary value problem is obtained by the solution of the [56]dual variational problem in which the first order variation of the functional vanishes. Choosing an approximate interpolation function (or shape function) for the field variable in the elements, the functional is expressed locally within each element in terms of the nodal-point values. The local equations are then assembled into the overall problem. Thus, the functional is approximated by a function of global nodal-point values. The condition for this function to be stationary results in the stiffness equations. These stiffness equations are then solved under appropriate boundary conditions. The basic mathematical descriptions of the methods, as well as the solution techniques, are given in many excellent books on the subject such as those written by Bathe, K.J.[56], Zienkiewicz, O.C. [82], as well as others that are listed in the bibliography section of this thesis. The main advantages of the finite element method are [19]:(a) The capability of obtaining detailed solutions of the mechanics of a deforming body, namely, velocities, shapes, strains, stresses, temperatures, or contact pressure distributions,(b) The fact that a computer code, once written, can be used for a large variety of problems by simply changing the input data. In the remainder of this chapter we will take in depth look at the flow formulation (rigid-plastic & rigid-plastic) FE model, and a less rigorous look at the elastic-plastic finite element model corresponding to the solid formulation. We will also study the FE model for the heat transfer part of this problem, as well as examine it to handles the coupling between mechanical and thermal portions of this complex problem. Finally, we will study the main non-linearities present in this highly non-linear problem.

4.1.1 Basic Procedure of Finite Element Method (FEM)

Most of the physical systems can be modeled by partial differential equations. The state variable in the system is assumed as a continuous function. A geometrically complex domain of the problem is divided into finite number of sub-domains called finite elements. The elements are interconnected by the common nodal points. An approximate interpolation function (or shape function) is chosen for the field variable in the elements. In the case of variational approach, proper functional is formulated depending upon the specific constitutive relations. The functional is expressed locally within each element in terms of the nodal point values. When the condition for this functional to be stationary is applied, it results in the stiffness equations. These stiffness equations are then solved using appropriate boundary conditions.

4.1.2 Variational Method Approach [The Finite Element Formulation]

Boundary value problems in continuum mechanics can be expressed in two different ways: the partial differential equations with the associated boundary conditions and the variational equations with the appropriate function space. The solutions of these two different forms of boundary value problems are referred to as the strong solution and the weak solution, respectively. The term weak is used in the sense that the requirement of continuity (differentiability) of solution is weakened in the variational form of boundary value problems. If a strong solution requires the existence of a second derivative, the corresponding weak solution requires only the existence of a first derivative in the sense of distribution; that is, the first derivative needs to be continuous within each of a finite number of sub domains but not necessarily across the interboundary between sub domains. The variational form of boundary value problems can be obtained only when the quadratic form of functional exists so that the set of Euler equations, obtained by the vanishing of the first variation of the functional, is identical to the original partial differential equations. However, the same form can be obtained by using the so-called weak formulation or the principle of virtual work, although certain mathematical features of variational problems with the quadratic functional such as the existence and uniqueness of solutions and the stability and accuracy of finite element solutions cannot be stated. Here, the weak formulation is used to accommodate abroad class of plastic constitutive models to the same framework of formulation. The constraint conditions such as the incompressibility condition and the contact condition can generally be incorporated into the variational formulation by using one of two techniques: the penalty method or the Lagrange multiplier method. The penalty method has the advantage of simple implementation, but it has a drawback such that it can result in an over constrained problem or an under constrained problem depending on the choice of the penalty parameter. The over constraint means the volumetric locking or the locking of contact surfaces, and the under constraint means the inaccuracy of solution in the sense of incompressibility or no penetration. On the other hand, the Lagrange multiplier method can avoid the drawback of the penalty method, but it has a disadvantage concerning the increase of problem size because the Lagrange multipliers are treated as additional solution variables such as the velocity of material particles. The Lagrange multiplier can be interpreted as the hydrostatic stress for the incompressibility constraint and the normal contact traction for the no penetration condition. In areas of metal forming simulation, it is popular to use the Lagrange multiplier method for the incompressibility condition and the penalty method for the contact condition. However, the penalty method has also been used successfully with a certain class of finite elements with the selective reduced integration scheme[41].In order to construct finite element approximations for the solutions of finite deformation problem it is necessary to write the formulation in a Galerkin (weak) or variational form [83]. A critical element in the finite element method is the identification of a variational statement equivalent to the governing differential equations. For a solid undergoing non-linear material deformation, a functional is to be identified for the variational statement [84]**.**The basis of finite-element metal-flow modeling, for example, using the variational approach is to formulate proper functional, depending upon specific constitutive relations [85].Out of the four approaches for the derivation of the basic equations for the finite-element analysis we have just stated in section 3.1, the variational method and the weighted residual method are the most commonly used for finite element flow modeling. The duality [41] of the boundary value problem and the variational problem can be seen clearly by considering the use of the functional [56].

$$\pi(u) = \int_a^b (x, u, \vee)\, d_x, a \leq x \leq b \qquad (4.2),$$

where the coordinate, u is the field variable and $\acute{u}$ is the derivative of u with respect to x. Then using the theory of calculus of variations, $\delta\pi$(u) = 0, breaks down into two parts, that of the domain, and that of the boundary as follows:

$$\delta\pi(u) = \int_a^b \delta F\, d_x = \int_a^b \left[\frac{\partial F}{\partial u}\,\delta u + \frac{\partial \acute{F}}{\partial \acute{u}}\frac{d(\,\delta u)}{d_x}\right] d_x \qquad (4.3)$$

Integrating the second term by parts, we have

$$\delta\pi(u) = \int_a^b \left[\frac{\partial F}{\partial u} - \frac{d}{d_x}\left(\frac{\partial F}{\partial \acute{u}}\right)\right] \delta u\, d_x + \left[\frac{\partial F}{\partial \acute{u}}\right]_a^b \qquad (4.4)$$

Thus, $\delta\pi(u) = \int_v \{Euler\ Equation\}\, \partial u dV + \{the\ boundary\ term\}$ (4.5)

The Euler equation is a differential equation taken over the domain V that is argued to be zero because of the arbitrariness of δ(u). Given the differential equations, the functional π and the boundary terms can often be constructed by manipulation. For our boundary value problem, the variational approach is based on one of two variation principles. It requires that "among admissible velocities[86] v_i that satisfy the conditions of compatibility and incompressibility, as well as the velocity boundary conditions, the actual solution give the following functional (function of functions) a stationary value [27,36, 38].

$$\pi = \int_V \bar{\sigma}\dot{\bar{\mathcal{E}}}dV - \int_{SF} F_i V_i dS \tag{4.6a}$$

For rigid-plastic materials, and

$$\pi = \int_V E(\dot{\varepsilon}_{ij})dV - \int_{SF} F_i V_i dS \tag{4.6b}$$

for rigid-plastic materials, where $\bar{\sigma}$ is the effective stress, $\dot{\bar{\mathcal{E}}}$ is the effective strain rate, F_i represents the surface tractions, and $E(\dot{\varepsilon}_{ij})$ is the work function, such that, $S_{ij} = \frac{\partial F}{\partial \dot{\varepsilon}_{ij}}$, where S_{ij} denote the deviatoric stresses" [56].The solution of the original boundary value problem is then obtained from the solution of the dual variational problem, where the first-order variation of the functional vanishes, namely[40,41],

$$\delta\pi = \int_V \bar{\sigma}\delta\, \dot{\bar{\mathcal{E}}}\, dV - \int_{SF} F_i \delta\, V_i dS = 0 \tag{4.7}$$

Where $\bar{\sigma} = \bar{\sigma}\,(\bar{\varepsilon})\; and\; \bar{\sigma} = \bar{\sigma}(\bar{\varepsilon}\,\dot{\varepsilon})$ For rigid-plastic and rigid viscoplastic materials, respectively.The incompressibility constraint on admissible velocity fields in Equation (4.7) may be removed by introducing a Lagrange multiplier λ and modifying the functional (4.6a) by adding the term $\int \lambda\, \dot{\mathcal{E}}_V\, d_v\; where\;\; \dot{\mathcal{E}}_V = \dot{\mathcal{E}}_{ii}$ is the volumetric strain rate [88]. Then,

$$\delta\pi = \int_V \bar{\sigma}\delta\, \dot{\bar{\mathcal{E}}}\, dV + \int_V \lambda\delta\dot{\mathcal{E}}_V\, dV + \int_V \dot{\mathcal{E}}_V \delta\lambda\, dV - \int_{SF} F_i \delta\, V_i dS = 0 \tag{4.8}$$

Another way of removing the constraint is to use the penalized form of the incompressibility [25, 27, 33, 34, 35, 36, 40, 51, 53,57,61,74 ,82] as

$$\delta\pi = \int_V \bar{\sigma}\delta\, \dot{\bar{\mathcal{E}}}\, dV + K\int_V \dot{\mathcal{E}}_V \delta\dot{\mathcal{E}}_V\, dV - \int_{SF} F_i \delta\, V_i dS = 0 \tag{4.9}$$

where K, is a large positive constant to penalize the dilatational [65,66] strain-rate, δv_i and $\delta\lambda$ are arbitrary variations, and $\delta\, \dot{\bar{\mathcal{E}}}$ and $\delta\dot{\mathcal{E}}_V$ are the variations in strain rate derived from, δv_i equation (5.8) or (5.9) is the basic equation for finite element formulation . An alternative approach to equation (5.8) is to begin with a weak form of the equilibrium equations, namely [10, 11,70]

$$\int_V \frac{\partial}{\partial X_j}\delta v_i\, dV = 0 \tag{4.10}$$

Where δv_i is an arbitrary variation in v_i equation (3.9) becomes $\int_V \frac{\partial(\delta v_i)}{\partial X_j} dV -$

$$\int_V \frac{\partial}{\partial X_j}\left(\sigma_{ij}\delta v_i\right) dV = 0 \qquad (5.11)$$

Which is the expression of the virtual-work principle, if δv_i is considered to be the virtual motion. Using the symmetry of the stress tensor and the divergence theorem, we have[35,36]

$$\int_V \sigma_{ij}\delta\dot{\mathcal{E}}_{ij} dV - \int_{SF} F_i \delta\, V_i dS = 0 \qquad (4.12)$$

For the surface integral term in (3.11), the boundary conditions that $\delta\, V_i = 0$ on S_v (essential boundary condition) and the traction $F_i = \sigma_{ij}n_j$ on S_F (4.13)

(Suppressible boundary condition), are imposed [56]**.** Substituting the expression for the Cauchy stress $\sigma_{ij} = S_{ij} + \sigma_m$ where $\sigma_m = \frac{1}{3}\sigma_{kk}$ is the hydrostatic or mean stress, into equation (3.11) gives

$$\int_V S_{ij}\delta\, \dot{\mathcal{E}}_{ij} dV + \int_V \sigma_m \delta\dot{\mathcal{E}}_{\mathrm{V}}\, dV - \int_{SF} F_i \delta\, V_i dS = 0 \qquad (4.14)$$

As a result the constitutive equation and the definition of $\dot{\bar{\mathcal{E}}}$, it is seen that, $S_{ij}\,\delta\, \dot{\mathcal{E}}_{ij} = \bar{\sigma}\delta\, \dot{\bar{\mathcal{E}}}$ and the final form of equation (5.14) suitable for finite element formulation becomes

$$\int_V \bar{\sigma}\delta\, \dot{\bar{\mathcal{E}}} dV + \int_V \sigma_m \delta\dot{\mathcal{E}}_{\mathrm{V}}\, dV - \int_{SF} F_i \delta\, V_i dS = 0 \qquad (4.15a)$$

with the incompressibility constraint given by $\dot{\mathcal{E}}_{\mathrm{V}} = 0$ inV. The incompressibility constraint is removed by modifying equation (5.15a) as

$$\int_V \bar{\sigma}\delta\, \dot{\bar{\mathcal{E}}} dV + \int_V \sigma_m \delta\dot{\mathcal{E}}_{\mathrm{V}}\, dV + \int_V \delta\sigma_m \dot{\mathcal{E}}_{\mathrm{V}}\, dV - \int_{SF} F_i \delta\, V_i dS = 0 \qquad (4.15b)$$

By comparison of equations (4.8) and (4.9) to Equation (4.15b), the lagrangian multiplier λ in equation (4.8) is identified as the mean or hydrostatic stress σ_m, where $\sigma_m = \frac{K}{2}\dot{\mathcal{E}}_{\mathrm{V}}$, thus providing the interpretation of K as a constant similar to the bulk modulus. Equation (4.8) or (4.9) is the basic equation for the finite element discretization. Once the solution of the velocity field that satisfies the basic equation is obtained, then corresponding stresses can be calculated using the flow rule and the known mean stress distribution [56].We will now look at the two main formulations used in the application of finite element analysis for metal forming, namely, the flow formulation and the solid formulation. Flow formulation assumes that the plastic deforming material has negligible elastic response, while it included in the solid formulation. Then we will develop the finite element equations for each of these two formulations, solid and flow, starting from equation (4.8) or (4.9) which as we have just seen is the basic equation for finite element formulation.

4.1.3 Finite Element Method for Metal Forming Simulation

The simulation processes was carried out using the commercial finite element software ,with the ABAQUS code 6.14 [3], applying the generalized plane strain procedure for modeling the 3D problem using a 2D formulation, reducing the computational cost time, in order to make the procedure really useful for producers[92]. Metal forming processes, such as rolling in general involve large inelastic deformation of the work piece. To investigate the hot rolling problem, finite elements can be divided into three categories; according to different basic assumptions about the behavior of the work piece material. These are plastic, rigid-plastic and elastic-plastic methods. They usually focus on: (a) deformation (stress, strain, strain rate, force, torque and friction). (b) Thermal-mechanical, microstructure, hear-transfer and temperature. (c) Optimum process [75] .A coupled thermo mechanical analysis of the large deformation problem is necessary to properly simulate such a process to find the effect of roller size and thermal effects on the rolling parameters using finite element analysis [7]. A number of metals have been noted to exhibit rate (time) dependent inelastic behavior at elevated temperatures [5].Awareness and understanding of the basic procedures to determine the flow stress, the frictional response and thermal contact resistances under different conditions of strain-rate and temperature are fundamental for improving the quality of data to be inserted in finite element computer programs since accuracy and reliability of numerical simulations are critically dependent on input data, the following sections will provide a brief overview of the most widespread experimental techniques that are utilized for material, friction and contact characterization. Modeling and simulation of hot rolling processes are tools to better understand and thereby solve new problems arising when forming new materials and geometries[67]. The bases for FE analysis of large deformation problems were not established until the mid 1970's, and it was not until then the first procedures for finite element simulation of metal forming were presented. Early attempts to simulate metal forming processes by means of the Finite Element method were usually based on 2D, or axisymmetric models. The 'flow' and the 'rigid-plastic' approaches were more popular than the 'solid' one, mainly because it was possible to advance the solution in much bigger increments in these approaches. The full version of these programs enables users to perform 2D or 3D simulations involving analyses of the following phenomena: mechanics (stress, strain distribution), heat transfer, phase transformation, and diffusion [54,68].The aim is that the simulation code should be able to simulate the complete forming process and to be able to unveil any possible defects. Metal forming simulations tend to be very time consuming. One reason for this is that the process itself is computationally very complicated, involving effects such as nonlinear material behavior, large deformations, and complicated contacts between tools and work piece. Another reason is that the FE models usually are very big, containing tens and hundreds of thousands elements. In the development of FE codes for metal forming simulation, Computational efficiency has therefore always been a primary concern [93]. Finite element method is a powerful tool that used to analyzing the metal forming processes with numerical modeling and simulation of metal forming processes. The simulations have replaced full scale process trials, thus reducing cost and lead-time. Numerical simulations are widely applied in research as well as in industrial practice (Altan 1996). Simulations of 2D problems are simpler, easier and more cost effective than 3D problems but produce almost accurate results[84].As observed by Lenard, Pietrzyk, & Cser, there are two major and distinct approaches to the simulation of metal forming processes. The first is the solid-state incremental approach, also known as solid formulation (considers finite deformation), which usually employs elastic-plastic material models. This approach uses a Lagrangian description of motion. The nodal displacements are the basic unknowns, which are related to the strains by the standard kinematic expressions or strain-displacement relationships [19]. The constitutive model used relates the stresses and the strains through stress-strain or constitutive relationships expressed in incremental form. The equilibrium equations can be written either as differential equations, to be satisfied in the volume and on the boundary of the body, or in a variational form as done by the principle of virtual work. The second approach, the flow formulation (based on infinitesimal deformation theory), uses the rigid-plastic material models [94]. Since in metal forming operations, the non-linear plastic strains are much larger than the elastic strains, these last ones are usually neglected allowing the use of a simpler rigid-plastic model in the analysis. The resulting constitutive equations in this approach are identical to those of a Non-Newtonian fluid**.** The constitutive equations now relate the stresses and the strain rates. Various constitutive models are used in the flow formulation. These include the Levy-Mises model used in rigid-plastic solutions, as well as plastic models such as the Norton-Hoff law[95] or the Sellars-Tegart law [19]**.**The main advantage of the flow formulation (rigid-plastic method) is that the power of deformation is calculated as a product of the invariants of the stress tensor and the strain rate tensor, making the solution insensitive to rotations. Also, the resistance of the material to deformation can be introduced as a function of the strain rate, strain and temperature and essentially any type of approximating function can be used. The rigid-plastic method is more suitable for the large, non-linear plastic deformations found in the hot rolling process [19,33].The original problem associated with the deformation process, of materials, is a boundary value problem. For the deformation process of rigid-plastic materials, flow formulation, the boundary-value problem is stated as follows: at a certain stage in the process of quasi-static distortion, the shape of the body, the internal distribution of temperature, and the current values of material parameters are supposed to be given or to have been determined already. The velocity vector is prescribed on a part of the surface vs. together with traction if on the remainder of the surface, FS. Solutions to this problem are the stress and velocity distributions that satisfy the governing equations and the boundary conditions. In the solid formulation approach, the boundary value problem is stated such that, in addition to the current states of the body, the internal distribution of the stress also is supposed to be known and the boundary conditions are prescribed in terms of velocity and traction-rate. Distributions of velocity and stress-rate (or displacement and stress-increment) are the solutions to this problem. The solid formulations of the finite element method for metal forming problems have been based on the use of the Prandtl-Reuss equations for elastic-plastic materials. The formulation is given in the rate form and assumes the infinitesimal theory of deformation. In analyzing metal-forming processes, however, the elastic-plastic finite element method with infinitesimal formulation has severe drawbacks. The large amount of rotation involved in metal forming rules out infinitesimal analysis. Furthermore, the nature of elastic-plastic constitutive equations requires short time steps in no steady-state analysis, a requirement that is severe when the body goes from elastic to plastic deformations. A simplified solution to this problem is given by the flow formulation where the elastic portion of deformation is neglected all plastic deformation is treated as a flow problem. The flow formulation of the finite element method for metal forming processes is based on the Levy-Misses plasticity model for rigid plastic materials, which assumes that work hardening is negligible. A very important improvement was the inclusion of the effects of strain-rate and temperature in material properties and of thermal-mechanical coupling, in the solution. This development has extended the finite element analysis into the hot metal working processes and allowed us to successfully model the hot rolling process since Finite element methods are capable of simulating the deformation of the metal in the roll gap and predicting the roll contact stresses, the total rolling load, and the torque of rolling. During the simulation that involves very large deformation, some elements become much more distorted and are not appropriate for further computation. Hence the model has the ability to regenerate the mesh several times in order to complete the simulation. Use of 3D tetrahedral elements with 30 mm mesh size is made. The tetrahedral mesh is found to suit the complex shapes in deformation and for automatic meshing and remeshing.The FEM mesh of the bloom consisted of 18300 nodes and 83973 elements. The rollers are considered as rigid body and meshed in 2D. The simulation was run on a 64GB RAM and 8 cores server. In the present work, the rolling mill roll configuration and the bloom were modeled using the Solid Edge software. In the present study the steel bloom of an original square cross section of 320 by320mm^2 with a length of 3000 mm is reduced to a desired thickness by rolling through the roll stand with the material properties of Carbon Steel-ASTM,A36 (mild steel) grade has been considered. To define the material grade, chemical composition, the physical properties, and flow stress data at elevated temperature are incorporated in the simulation. With the above common input parameters and boundary condition, the metal deformation behavior simulated at various the initial stages of single roll pass [95].

4.1.4 The Rigid Plastic Finite Element Model (RPFEM) Formulation (Flow Rule)

The RPFEM based on a Lagrange multiplier was used to analyze the plastic deformation of work pieces in roll gap. The RPFEM can be inferred from the variation principle of rigid-plastic material[96].During stress and strain model under hot rolling condition elastic deformation, in metal forming operation, is very small or recoverable strain is ignored because of its limited possible magnitude [81]as compare to plastic deformation and can be neglected in order to consider the formulation as a rigid-plastic one or so far, only the inelastic part of the strain rate has been considered [87]. The rigid-plastic flow analysis is an approach to large deformation analysis, which can be used for metal forming problems [54] such as hot rolling. The three-dimensional form may be reduced to a two-dimensional form if loading, geometry, and material behavior do not vary with a third coordinate [97].The rigid-plastic formulation takes into account only the inelastic ($\dot{\varepsilon}^p \ or \ \dot{\varepsilon}^i$) contribution to the total strain rate, ignoring the elastic ($\dot{\varepsilon}^e$) part [84]:

$\dot{\varepsilon} = \dot{\varepsilon}^e + \dot{\varepsilon}^p or \ \dot{\varepsilon}^i + \dot{\varepsilon}^e$……………………………………………..……………….. (4.16)

The flow formulation is based on the [93] quasi-static equilibrium equations, which in the absence of body forces and after some mathematical treatment that takes into consideration the natural and essential boundary conditions, can be written as**.**

$$\int_V \sigma_{ij} \delta \dot{\varepsilon}_{ij} dV - \int_S t_i \delta u_i dS = 0 \qquad (4.17)$$

Where V is the domain volume, S is the boundary surface where tractions $t_i = \sigma_{ij} n_j$ are applied and $\dot{\varepsilon}_{ij}$ are the components of the strain rate tensor.

$$\dot{\varepsilon}_{ij} = \frac{1}{2}\left(u_{i,j} + u_{j,i}\right) \qquad (4.18)$$

In the flow formulation, velocities ui are the primary unknown instead of displacements, there is no strain tensor and the stress σij is directly related to the strain rate by means of rigid plastic constitutive equations. In case of using the von Mises yield criterion, also called the "distortion energy criterion",

$$\int \left(\sigma_{ij}\right) A = \frac{1}{2} \sigma_{ij}' \sigma_{ij}' \qquad (4.19)$$

The incompressibility constraint is satisfied exactly by updating the thickness. This capability is not available for steady state analysis. According to Lenard & Pietrzyk, two formulations are available: Eulerian (steady state) and Lagrangian (transient). The effects of elasticity are not included in the R-P formulation. The rigid-plastic formulation needs to enforce the incompressibility condition, which is inherent to the strictly plastic type of material response being considered. Incompressibility may be imposed in three ways[65]:

Langrage Multipliers: - Such procedure requires Herrmann elements which have a pressure variable as the Lagrange multiplier.

Penalty functions: - This procedure uses regular solid elements, and adds penalty terms to any volumetric strain rate that develops. It is highly recommended that the constant dilatation formulation be used – by entering a nonzero value in the second field of the geometry model definition option. Penalty factor can be treated as constant or variable through the R-P FLOW parameter. The penalty value is entered through the parameters option.

$\rightarrow K = \frac{E}{6(1-2V)}(one\ half\ of\ the\ bulk\ modulus)$

Updating the thickness (for plane stress analysis):- the incompressibility constraint is satisfied exactly by updating the thickness. This capability is not available for steady state analysis.

The rigid-plastic flow formulation is based on iteration for the velocity field in an incompressible, non-Newtonian fluid. Elastic deformation, in metal forming operation, is very small as compare to plastic deformation and can be neglected in order to consider the formulation as a rigid plastic [20,61].The fundamental for the analysis of metal forming processes and the governing equations for the solution of the mechanics of plastic deformation of the rigid plastic materials are summarized as follows. The constitutive equations and the normal flow condition for a nonzero strain rate is given by the Levy-Mises flow rule that can be expressed as [12,13,14, 34,38,39,55,74]

$$\dot{\varepsilon}_{ij} = \frac{3}{2}\frac{\dot{\bar{\varepsilon}}}{\bar{\sigma}} \tag{4.20}$$

where

$\dot{\bar{\varepsilon}} = \sqrt{\frac{2}{3}\ \dot{\varepsilon}_{ij}\ \dot{\varepsilon}_{ij}}$ is the equivalent strain rate, and $\bar{\sigma} = \sqrt{\frac{3}{2} s_{ij} s_{ij}}$ is the equivalent stress (which may be rate dependent) and $s_{ij} = \sigma_{ij} - \frac{1}{3}\delta_{ij}\sigma_{kk}$ gives the deviatoric stress.The effective viscosity is evaluated as $\mu = \frac{2}{3}\frac{\bar{\sigma}}{\dot{\bar{\varepsilon}}}$ and so when $\dot{\bar{\varepsilon}} \rightarrow 0, \mu \rightarrow \infty$ and we then have rigid plasticity. In rigid plastic flow analysis, several iterations are required at any given increment, the greatest number occurring in the first increment. Subsequent increments require less iteration, since the initial iteration can make use of the solution from the previous increment. Due to the simplicity of the rigid plastic formulation, it is possible to bypass stress recovery for all iterations but the last in each increment, provided that the displacement control is used[35,74]. In such cases, considerable savings in execution time are achieved [19].The Steady-State rigid-plastic flow formulation is based on an eulerian reference system. The nodal coordinates are updated at the end of a step according to the relation

$$x_i{}^n = x_i{}^{n-1} + \dot{u}_i{}^n \Delta t \quad (4.21)$$

Where n refers to the step number, $\dot{u}_i{}^n$ is the nodal velocity component, and Δt is an arbitrary time step. Δt is selected in such a way as to allow only a reasonable change in mesh shape while ensuring stability with each step. Updating the mesh requires judicious selection for a time step. This requires some knowledge of the magnitude of the nodal velocities that will be encountered. The time step should be selected such that the strain increment is never more than one per cent for any given increment [65]. In the transient (Lagrangian) analysis procedure, there is an automatic updating of the mesh at the end of each increment. During the analysis, the updated mesh may exhibit severe distortion and the solution may be unable to converge. Mesh rezoning must be used in that case to overcome this difficulty[65]. With respect to the hot rolling problem, the development of computational techniques allowed the finite element method to simulate both thermal and mechanical events in the deformation zone. The first application of the finite element method to analyze the temperature distribution during hot rolling appears to be due to Zienkiewicz in1981.The rigid-plastic flow FEM model described here is based on the work by Kobayashi et al[56]and by Pietrzyk and Lenard[58] and contains two parts. The first part determines the velocity field, the strain rate and the strain fields using the rigid plastic FE approach. The second part deals with heat transfer and heat generation within the strip. Rigid-Plastic finite element models are the most efficient tools in the simulation of metal forming processes and it gives very accurate results for hot rolling. They combine the accuracy of the finite-element technique with reasonable computing times and memory requirements. The rigid plastic approach is based on an extremum principle which states that for plastically deforming body of volume, under traction F_i, prescribed on a part of the surface s_F , and the velocity $\bar{v}$ prescribed on the remainder of the surface s_V, under the constraint $\dot{\varepsilon}_{ij} = 0$ the actual solution minimizes the functional [55] and given by equation (4.22), as

$$\pi = \int_V \bar{\sigma}\, \dot{\bar{\mathcal{E}}} dV + \int_V \dot{\lambda} \mathcal{E}_{\mathrm{V}}\, dV - \int_{SF} F_i V_i dS \quad (4.22)$$

Where

$\lambda =$ Lagrange multiplier (equal to the mean stress $\sigma_m, \overline{\sigma} =$ Equivalent or effective stress

$, \dot{\bar{\varepsilon}} = \sqrt{\frac{2}{3}\, \dot{\varepsilon}_{ij}\, \dot{\varepsilon}_{ij}} = equivalent\ or\ effective\ strain\ rate,$

$\dot{\bar{\varepsilon}} = \sqrt{\frac{2}{3}\, \dot{\varepsilon}_{ij}\, \dot{\varepsilon}_{ij}} = equivalent\ or\ effective\ strain\ rate,\ \dot{\varepsilon}_v = volumetric\ strain\ rate.$

In the flow theory of plasticity, strain rates are related to stresses by the flow rule associated with the criterion of Levy-Mises

$$S_{ij} = \frac{2}{3}\frac{\overline{\sigma}}{\dot{\bar{\varepsilon}}}\dot{\varepsilon}_{ij} \tag{4.23}$$

A numerical approach that aims to model the process of shape rolling has to face a highly non-linear physical problem. The non-linearity has its origins in both kinematic and material effects such as:- Complex 3D shape, large displacements, large rotations and large strains, elastic-plastic material behavior with thermal and viscous effects, time-dependent material behavior due to evolution of microstructure, contact and friction. The finite-element method has been recognized as a numerical approach that is well capable of solving such problems. Two basic formulations are adopted in the non-linear FEM to deal with the large displacements, rotations and strains. These are Lagrangian and Eulerian formulation [56].In the Lagrangian formulation the mesh is fixed to the material and follows its movements. Using this formulation free surface is traced naturally and deformation history can easily be taken into account. The disadvantage of the formulation is that the mesh can become distorted due to the large deformation. The distortion leads to decreased accuracy of the results or even to a premature end of the calculation. To address the problem, a remeshing procedure can be used, in which the old mesh is replaced by a new one. Critical issues in the application of remeshing are the automatic mesh generation and the accuracy of the transfer of information between the old and new meshes. In the Eulerian formulation the mesh is fixed in the space and the material flows across the elements. Since the mesh does not move, the distortion is not an issue here. In general, the material boundaries are not equal to the element edges and special procedures are required to trace the free surfaces as well as boundaries between different materials, including contact. Also the transfer of material properties must be taken into account. Most of the metal-forming processes involve modification of free surfaces and contact. Thus, the majority of the finite element model codes for the simulation of metal-forming have applied the lagrangian formulation or better the updated lagrangian formulation. The term updated means that all variables are referred to the last calculated (updated) configuration, Bathe [6].Some of the first applications of 3D finite element methods for simulation of shape rolling appeared in the late1980s. The codes used both elastic-plastic and rigid-plastic material formulations and assumed isothermal rolling process. In the mid-1990s, the developments in computer technology and finite element methods reached a level when larger 3D simulations became feasible. At this point Corus launched a project, which resulted in development of a roll-pass design system based on ABAQUS finite element software. The system has some advanced features such as thermo-mechanical coupling and an adaptive meshing algorithm based on the arbitrary lagrangian Eulerian formulation. The ALE formulation is a combination of the lagrangian and Eulerian descriptions. In such a formulation the mesh displacement is not necessarily equal to the material displacement nor equal to zero, but can be chosen independently from the material displacement. The ALE formulation can be used to solve problems with free surfaces in an Eulerian formulation or to avoid grid distortion in a Lagrangian formulation. In general, a rolling-pass simulation is a transient analysis that includes actual threading of the work piece through the roll gap. The analysis is run until a steady-state solution is reached, which means that a constant shape of the work piece is observed at the exit of the roll gap. Such an approach emanates from the application of lagrangian formulation. An alternative approach uses a mesh that is an initial guess of the final configuration. Then the flow of the material through the mesh is calculated using the Eulerian formulation. The calculation is terminated when the configuration of free surfaces has converged. The crucial point for the steady-state approach is the prediction of free surfaces and the tracing of properties for history dependent materials. Due to the ability to correctly describe the free surfaces, the ALE formulation was applied in a steady-state analysis of shape rolling and slitting rolling. Shape rolling is a coupled thermo-mechanical problem, where the material properties strongly depend both on temperature and strain rate. The interaction between the mechanical and thermal field can be solved within one time step leading to simultaneous solutions. However, this approach is often associated with high computational cost. Alternatively, staggered solution technique is used, where the mechanical problem is solved at a fixed temperature, followed by the solution of thermal problem at a fixed configuration. The latter approach is commonly applied in thermo-mechanical analysis of shape rolling ,[65] but also in general purpose finite element codes such as MSC[65]. Beside the fully 3D finite element analysis of shape rolling, simplified methods were developed in effort to minimize the computational costs. They assumed that the longitudinal displacement is uniform over any cross-section perpendicular to the rolling direction. The method combined the slab method, to impose the force equilibrium in the rolling direction, and 3D rigid-plastic finite element method, to analyses the lateral spread and elongation of the bloom. They replaced the 3D finite element model with a 2D finite element model with generalized plane-strain formulation, reducing the size of models even more. The temperature was predicted by 2D FEM neglecting the temperature gradient in the rolling direction. The method was also coupled with a thermal model using a 2D FEM. Today, the simplified methods are still being used. They are applied in analyses of multi-pass shape rolling, where they provide approximations of the displacement and temperature field for complex material models. Such models are often physically-based material models that predict the evolution of mechanical properties, such as flow stress, together with micro structural changes. In this study, simulations of bloom rolling are performed using both 3D FEM and a simplified method combining the slab method and 2D FEM [56]. The generalization to three dimensions of the quadrilateral used in two dimensions [97] for the discretization of the functional π is performed in a typical finite element manner using four node quadrilateral elements (linear isoperimetric element) for discretization as shown in Figure 23.

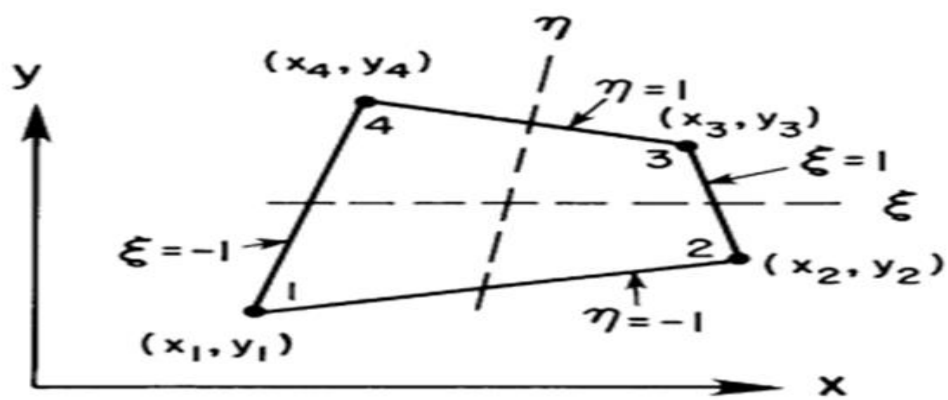


Figure4. 5: Quadrilateral element and natural coordinate system.

The geometry of an element, in general, is uniquely described by a finite number of nodal points also called as nodes[56]. These nodes are located either on the boundary of the element or within the element. The shape function defines an admissible velocity field locally in terms of velocities associated with the nodes. Thus elements are characterized by the shape and the order of shape functions. In this study 4-noded rectangular elements are used. The velocity field $\overline{v}$ inside the element is approximated by shape functions in terms of nodal point velocity values as

$$\bar{v} = \begin{bmatrix} v_x \\ v_y \end{bmatrix} = N^T v \tag{4.24}$$

where $v = \{v_1 v_2, \ldots\ldots, v_8\}^T$ is the vector of nodal velocities (4 nodes x 2 DOF/node) N is the matrix of shape functions N_1, N_2, N_3, N_4which for four node elements and plane strain is

$$N^T = \begin{bmatrix} N_1 & 0 & N_2 & 0 & N_3 & 0 & N_4 & 0 \\ 0 & N_1 & 0 & N_2 & 0 & N_3 & 0 & N_4 \end{bmatrix} \tag{4.25}$$

With the odd-numbered and even-numbered velocities correspond to the components, respectively. The plane strain discretization is similar to the above. The N; are the finite element shape functions, which for an isoparametric quadrilateral element are [32, 35, 38, 40, 58, 65, 66,74,75]

$$\begin{aligned} N_1 &= \tfrac{1}{4}(1-S)(1-t), \quad N_2 = \tfrac{1}{4}(1+S)\ (1-t) \\ N_3 &=, \tfrac{1}{4}(1+S)(1+t), \quad N_4 \ = \tfrac{1}{4}(1-S)(1+t) \end{aligned} \tag{4.26}$$

Where S and t represent a natural coordinate system. It is also necessary to discretize the strain-rate versus velocity relations or similarly, a discretization of the external traction yields

$$\bar{F} = \begin{bmatrix} T_x \\ T_y \end{bmatrix} = N^T F \tag{4.27}$$

Where F= $vector\ of\ the\ nodal\ values\ of\ the\ friction\ stress.$

It is convenient to arrange the strain-rate components in a vector form. For plane Strain $\dot{\varepsilon}_z = 0$

$$\dot{\varepsilon} = \begin{bmatrix} \dot{\varepsilon}_x \\ \dot{\varepsilon}_y \\ \dot{\gamma}_{xy} \end{bmatrix} = \begin{bmatrix} \frac{\partial v_x}{\partial x} \\ \frac{\partial v_y}{\partial y} \\ \frac{\partial v_y}{\partial x} + \frac{\partial v_x}{\partial y} \end{bmatrix} = \mathrm{Bv} \tag{4.28}$$

which gives us a relationship between the strain rates field inside the element and the nodal velocities and where B is the matrix of the derivatives of shape functions given by [26,28, 30, 38,40].

$$B = \begin{bmatrix} \frac{\partial N_1}{\partial x} & 0 & \frac{\partial N_2}{\partial x} & 0 & \frac{\partial N_3}{\partial x} & 0 & \frac{\partial N_4}{\partial x} & 0 \\ 0 & \frac{\partial N_1}{\partial x} & 0 & \frac{\partial N_2}{\partial x} & 0 & \frac{\partial N_3}{\partial x} & 0 & \frac{\partial N_4}{\partial x} \\ \frac{\partial N_1}{\partial x} & \frac{\partial N_1}{\partial x} & \frac{\partial N_2}{\partial x} & \frac{\partial N_2}{\partial x} & \frac{\partial N_3}{\partial x} & \frac{\partial N_3}{\partial x} & \frac{\partial N_4}{\partial x} & \frac{\partial N_4}{\partial x} \end{bmatrix} \tag{4.29}$$

The volumetric strain rate $\dot{\varepsilon}_v$ is expressed by [56]

$$\dot{\varepsilon}_v = \dot{\varepsilon}_x + \dot{\varepsilon}_y = C^T v \tag{4.30}$$

Where

$$C^T = \{1 \quad 1 \quad 0\}\, B \tag{4.31}$$

The effective strain rate, $\dot{\bar{\varepsilon}}$ in a discrete form is expressed by[56]

$$\dot{\bar{\varepsilon}} = \sqrt{\dot{v}^2 D \dot{\varepsilon}} = \sqrt{v^T B^T D B v} = \{P = B^T D B\} = \sqrt{v^T P v} \tag{4.32}$$

The matrix D is given by $D = \begin{bmatrix} \frac{2}{3} & 0 & 0 \\ 0 & \frac{2}{3} & 0 \\ 0 & 0 & \frac{2}{3} \end{bmatrix}$ (4.33)

During discretization, the volume V of the body is divided into n_e elements connected at n_n nodes. The functional for a single element is given by equation (4.22). Substituting components and expressing in matrix form,

$$\pi = \int_V \bar{\sigma} \sqrt{v^T P v}\, dV + \int_V \lambda C^T v\, dV - \int_{SF} N^T F N v\, dS \tag{4.34}$$

The functional for the whole deforming domain is the sum of the functional for the elements. This functional is discredited and a set of nonlinear simultaneous equations (stiffness equations) is obtained from the arbitrariness of δv and δλ as follows

$$. \frac{\partial \pi}{\partial v} = 0 \; and \; \frac{\partial \pi}{\partial \lambda} = 0 \tag{4.35}$$

Differentiation of the functional π with respect to the nodal velocities and to the Lagrange multiplier at the elemental level and assembling them into the global equation under appropriate constraints yields the stiffness equations:

$$\frac{\partial \pi}{\partial v} = \sum_j \left[\int_{Vj} \frac{\bar{\sigma}}{\dot{\bar{\varepsilon}}} v^T P v\, dV + \int_{Vj} \lambda C^T dV - \int_{SFj} N^T F N dS \right] = 0 \tag{4.36}$$

$$\frac{\partial \pi}{\partial \lambda} = \sum_j \left[\int_{Vj} C^T v\, dV \right] = 0 \tag{4.37}$$

These last two equations form a set of non-linear equations with nodal velocities v and Lagrange multiplier λ as unknowns, where j indicates the quantity at the j^{th}element. The solution is obtained iteratively by using the Newton-Raphson method. The method consists of linearization and application of convergence criteria to obtain the final solution. Linearization [88] is achieved by Taylor expansion near an assumed solution point v= v_0 (initial guess), namely

$$\left[\frac{\partial \pi}{\partial v_i}\right]_{v=v_0} + \left[\frac{\partial^2 \pi}{\partial v_j}\right]_{v=v_0} \Delta v_j = 0 \qquad (4.38)$$

Where Δv_j is the first-order correction of the velocity v_0 equation (4.36) can be written [88] in the form .

$$\mathrm{K}\Delta v = f \qquad (5.39)$$

Where K is called the stiffness matrix and f is the residual of the nodal point force vector[79]. Once the solution of Equation (4.39) for the velocity correction Δv is obtained, the assumed velocity is updated according to $v_0 = \alpha\Delta v$, where α a constant between 0 and 1 is called deceleration coefficient.

4.1.5 The Rigid-Plastic Model: Flow Formulation Approach

Rigid-plastic analysis is more advantageous for computational efficiency and robustness than elasto-plastic analysis is. This method has been used predominantly for the majority of bulk forming processes where the elastic deformation is negligible compared with the plastic deformation and the distribution of residual stresses is not of major concern. By neglecting the elastic portion of deformation, the rigid-plastic formulation turns out to be very similar to that of fluid flow problems except for the presence of yielding and so it is sometimes called the flow formulation. The velocity field satisfying the equilibrium equations, constitutive equations, and boundary conditions instantaneously is obtained at each state in the course of deformation [41].Most of the more common constitutive laws for idealizing real materials have been obtained from experimental approaches. The approaches show that the deformed metals exhibit temperature, strain and strain rate sensitivity. A material behavior that exhibits rate sensitivity is called plastic [57].There are a number of materials that exhibit plastic behavior. They include most metals at high temperature, super plastic materials, heated glass, and polymers. When the deformation is large, most of them can be considered to be rigid-plastic. This is the case of the hot rolling problem. Because of the importance of the application of plastic behavior to the metal-forming processes, several researchers have examined the treatment of time-dependent material behavior within the framework of the theory of plasticity. Zienkiewicz has shown the feasibility of the finite element approach in the deformation analysis of rigid-platic materials by treating them as non-Newtonian viscous fluids [19]. Others have applied this formulation to creep forming. The yield stress in the Levy-Mises flow rule is given in the form of a strain-hardening curve. In hot deformation processes, the majority of metals are also sensitive to changes of temperature and strain rate, and the influence of these parameters is often much stronger than the influence of strain. The behavior of these materials is well described by rigid-plastic flow and also by the plastic flow rule, which is expressed by a plastic potential. Two commonly used plastic laws are the Norton-Hoff law and the Sellars-Teggart law [57]. The Norton-Hoff Law, also known as plastic power law, was first used for uniaxial creep analysis by Norton in 1929 and extended to three dimensional analyses by Hoff in 1954[59]. It is generally written in the form [45, 85]:-

$$\overline{\sigma} = 2K\left(\sqrt{3\dot{\varepsilon}_\iota}\ \right)^{m-1\,\dot{\bar{\varepsilon}}} \tag{4.41}$$

and the monodimensional expression is

$$\overline{\sigma} = 2K\left(\sqrt{3\dot{\varepsilon}_\iota}\ \right)^{m+1\,\dot{\bar{\varepsilon}}} \tag{4.42}$$

We observe that

m=1 corresponds to the Newtonian fluid with a viscosity $\eta = K$,M=0 is the plastic flow rule for a material obeying the Levy-Mises yield criterion with a yield stress $\sigma_y = \sqrt{3K}$,0 $<$ m $>$ 1 is the first approximation for hot forming of metals. For most common metals m lies between 0.1 and 0.2 but for a super plastic material it can reach values between 0.5 and 0.7.The Sellars-Teggart Law for three-dimensional problems is written as (Sellars & Teggart, 1972):

$$\overline{\sigma} = \frac{2}{3\alpha}\sin h^{-1}\left(\frac{\dot{\varepsilon}_\iota}{A}\right)\frac{\dot{\bar{\varepsilon}}}{\dot{\varepsilon}_\iota} \tag{4.43}$$

Analysis of both laws shows that the second derivative of the plastic potential tends to infinity when the strain rate tends to zero. Therefore, a normalized Norton-Hoff law is suggested:

$$\overline{\sigma} = 2K\left(\sqrt{3}\ \right)^{m-1}\left({\dot{\varepsilon}_\iota}^2 + {\dot{\varepsilon}_\iota}^2\right)^{\frac{m-1}{2}}\dot{\bar{\varepsilon}} \tag{5.44}$$

Where $\dot{\varepsilon}_\iota = small\ constant\ such\ that\ if\, \dot{\varepsilon}_\iota >> \dot{\varepsilon}_0$ Equation (3.38) becomes nearly identical to Equation (3.36) and when $\dot{\varepsilon}_\iota << \dot{\varepsilon}_0$, the constitutive law tends to become purely Newtonian [58]. Plastic material models are commonly used in the finite element simulations of metal forming processes. The domain V is discretized into finite elements in the usual way. The unknown velocity field is discretized and an analytical description of this field within an element is obtained by the interpolation $\overline{v} = Nv$.The general form of the plastic functional for the Norton-Hoff law, after discretization is:

$$\pi = \int_V \frac{K}{m+1} \left(\sqrt{3\dot{\varepsilon}_\iota}\right)^{m+1} dV + \int_v \lambda\, \dot{\varepsilon}_\mathrm{l} v dV - \int_{SF} F_i v_i dS \qquad (4.\ 45)$$

Differentiation of the functional with respect to the nodal velocities yields a set of nonlinear equations, which is usually solved by the Newton-Raphson method [57].

4.1.6 Heat Transfer Finite Element Modeling in Rolling

A complete analysis of the rolling process also requires the simulation of heat transfer in the roll gap, making it necessary to couple the solution for the flow formulation with the thermal model. Temperatures are calculated, accounting for heat conduction in the material, heat generation due to plastic work, friction, and heat losses due to transfer to the surrounding medium. According to Kobayashi, Oh, & Altan, the importance of temperature calculations during a metal forming process has been recognized for a long time. Until recently, the majority of the work had been based on procedures that uncoupled the problem of heat transfer from the metal transformation problem. Several researchers have used this approach. They determined the flow velocity fields in the problem either experimentally or by calculations, and then they used these fields to calculate heat generation**”** [98]**.**In order to handle a coupled thermo-plastic deformation problem, it is necessary to solve simultaneously the material-flow problem for a given temperature distribution and the heat transfer equations. Zienkiewicz et al [94]discussed numerical solutions of such forming problems, with examples of steady flow in extrusion, drawing, rolling, and sheet metal forming. Kobayashi[56] developed the method for a coupled analysis of transient plastic deformation and heat transfer applied to solid cylinder compression and ring compression. The general diffusion equation is[57].

$$\frac{\partial y}{\partial x}\left(K\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(\frac{\partial T}{\partial z}\right)+q-C_p\dot{\rho}\frac{\partial T}{\partial t}=0 \qquad (4.46)$$

Where k = heat conduction coefficient T = temperature (K) $\dot{q}=\eta\overline{\sigma}_{ij}\overline{\dot{\varepsilon}_{iJ}}$ =rate of heat generation (W/m3 Cp = specific heat (J/kg K) , material's density (kg / m3) t = time (s).Solution of the diffusion equation must satisfy the specified boundary conditions . Along the boundaries of the deforming material, either the temperature T is prescribed or a heat flux is given. As explained by [56] in their derivation, the energy balance Equation (5.46) can be written in the form

$$\int_V K\frac{\partial^2 T}{\partial x_i}\delta T dV-\int_v C_p\rho\frac{\partial T}{\partial t}\delta T dV-\int_v \eta\overline{\sigma}_{ij}\dot{\overline{\varepsilon}}_{ij}\delta T dV=0 \qquad (4.47)$$

for arbitrary variation in temperature δT . By using the divergence theorem, equation(4.47) becomes[35,48,73]

$$\int_V K\frac{\partial^2 T}{\partial x_i}\delta\left(\frac{\partial y}{\partial x_i}\right)dV-\int_v \rho C_p\frac{\partial T}{\partial t}\delta T dV-\int_v \eta\overline{\sigma}_{ij}\dot{\overline{\varepsilon}}_{ij}\delta T dV-\int_{S_q} q_n\delta T dS=0 \qquad (4.48)$$

where q_n is the heat flux across the boundary surface S_q denotes the unit normal to the boundary surface and $q_n=K\frac{\partial T}{\partial n}$ (4.49)

Solutions to problems of this nature require the temperature field to satisfy the prescribed boundary temperatures and Equation (4.47) for arbitrary perturbation .For the finite element formulation the temperature field in Equation (4.48) is approximated by

$$T=\sum_\alpha q_\alpha T_\alpha=N^T T\,A \qquad (4.50a)$$

Where q_α the shape is function and T_α is the temperature at α^{th}. With the quadrilateral element shown in Figure 3.3

$$,N^T=\{q_1,q_2,q_3,q_4\} \qquad (4.50b)$$

$$T^T=\{T_1,T_2,T_3,T_4\} \qquad (4.50c)$$

Where q_1,q_2,q_3,q_4 are given by equations (4.26).

$$M=\begin{bmatrix}\frac{\partial q_1}{\partial x} & \frac{\partial q_1}{\partial y}\\ \frac{\partial q_2}{\partial x} & \frac{\partial q_2}{\partial y}\\ \frac{\partial q_3}{\partial x} & \frac{\partial q_3}{\partial y}\\ \frac{\partial q_4}{\partial x} & \frac{\partial q_4}{\partial y}\end{bmatrix} \qquad (4.51)$$

and substituting equation (4.50a-c) into Equation (4.48).

$$\sum_j \left[\int_{V_i} K\delta T^T MM^T T dV - \int_{V_i} \rho C_p \delta T^T NN^T \frac{\partial T}{\partial t} dV - \int_{V_i} \eta \left(\overline{\sigma}_{ij}\dot{\overline{\varepsilon}}_{ij}\right) T^T N dV - \int_{S_{q_i}} q_n \delta T^T N dS = 0\right] \quad (4.52)$$

Because of the arbitrariness of δT, the following system of equations is obtained[36,75],

$$\sum_j \left[\int_{V_i} KMM^T dVT + \int_{V_i} \rho C_p NN^T dV \frac{\partial T}{\partial t} - \int_{V_i} \eta \left(\overline{\sigma}\,\dot{\overline{\varepsilon}}\right) N dV - \int_{S_{q_i}} q_n N dS = 0\right] \quad (3.47)(4.53)$$

The set of equations given by (5.53) can be expressed in the form

$$C\dot{T} + K_c T = Q \quad (4.54)$$

Where C is the heat capacity matrix, K_c is the heat conduction matrix, Q is the heat flux vector is the vector of nodal point temperatures, and $\dot{T}$ the vector of nodal point temperature-rates. The heat flux vector Q in equation (3.48) has several components and is expressed with the interpolation function N by

$$Q = \int_V \eta \left(\overline{\sigma}\,\dot{\overline{\varepsilon}}\right) N dV + \int_{S_{rad}} \sigma\varepsilon ({T^4}_w - {T^4}_\infty) N dS + \int_{S_{conv}} h(T_w - T_\infty) N dS + \int_{S_{cond}} K(T_w - T_R) N dS + \int_{S_{cond}} q_{fr} N dS \quad (4.55)$$

The first term on the left is the heat, generated by plastic deformation inside the deforming body. The second term defines the contribution of the heat radiated from the work piece to the environment, where σ is the Stefan-Boltzmann constant, ε is the emissivity, and $T_w$and $\sigma T_\infty$are the work piece and the environment temperatures respectively which for hot rolling is approximately 0.8. The third term describes the heat convected from the body surface to the environment fluid (air or water) with heat convection coefficient h. The fourth term represents the contribution of the heat conducted from the work piece to the rolls through their interface and k is the work piece-roll heat transfer conduction coefficient. The last term is the contribution of the heat generated by friction along the roll-work piece interface, qf being the surface heat generation rate due to friction. The theory necessary to integrate (4.55) can be found in numerical analysis books. See for instance [73]**.** The convergence of a scheme requires consistency and stability. Consistency is satisfied by an approximation of the type [56]

$$T_{t+\Delta t} = T_t + \Delta t\left[(1-\beta)\dot{T}_t + \beta \dot{T}_{t+\Delta t}\right] \quad (4.56)$$

Where β is a parameter varying between 0 and 1, and t denotes time. For unconditional stability, β should be greater than 0.5. Selection of a proper value of β is an important factor in situations where it is desirable for the time step to be as large as possible; provided that the increments in strain are compatible with an infinitesimal analysis [73]**.**With respect to the computational procedures for thermo-plastic/viscoplastic analysis, we will treat the work piece and the rolls separately, assuming that the die properties do not change. Thus we greatly reduce the number of equations to be solved simultaneously, which, in turn, reduces the cost of the solution. There is no internal heat generation in the roller and therefore, the deformation calculations are not necessary. The heat generated through friction,$q^{"}fr$, is evenly distributed between the roller and the deforming material, and is calculated as

$$q^{"}_{fr} = \sigma_{fr}.v_r\xi \ \left({W}/{m^2}\right) \tag{4.57}$$

Where $\sigma_{fr} = \ friction\ stress\ (MPa),\ v_r$ =relative sliding velocity between the roll and the work piece (m/s), ξ=fraction of friction energy that is converted to heat. It should be noted that the nodes on the die do not generally coincide with those on the deforming material along the interface, and that the calculation of nodal point temperatures requires interpolation. When boundary conditions such as the convection term in Equation (4.55) apply, they are split into two parts: one containing the unknown temperatures is added to the heat conduction matrix K_c. Boundary conditions such as the radiation term in Equation (4.55) are applied using previous iteration values for body temperatures [8,13].The model just described can be used to calculate the temperature distribution as well as the velocity, strain rate, strain and stress fields in the deformation zone during hot rolling. Plane strain state is assumed in the velocity field and four node quadrilateral elements are used in the non-linear finite element model.

4.1.7 Coupled Thermal-Mechanical Analysis

The coupling between the deformation analysis and the heat analysis of the Work piece is given through the material constitutive relationship for the work piece. This is because for a rigid-thermo-plastic material, the flow stress is a function of effective strain, effective strain rate and temperature .Further, the problem of thermal analysis consists of two parts, the thermal analysis of the work piece and that of the roller [57].From the physical point of view, the rolling process is a coupled thermal-mechanical problem. The coupling between the mechanical and thermal phenomena results from the pressure-dependent thermal contact resistance between the steel strip and the rolls. Many operations performed in the metal forming industry (such as casting, extrusion, rolling, and stamping) can require a coupled thermo-mechanical analysis. The observed phenomena must be modeled by a coupled analysis if the following conditions pertain: First, coupling occurs when deformations result in a change in the associated heat transfer problem. Such a change can be due to either large deformation or contact. The second cause of coupling is heat generated due to inelastic deformation. The irreversibility of plastic flow causes an increase in the amount of entropy in the body, which in turns results in changes to the associated mechanical problem.

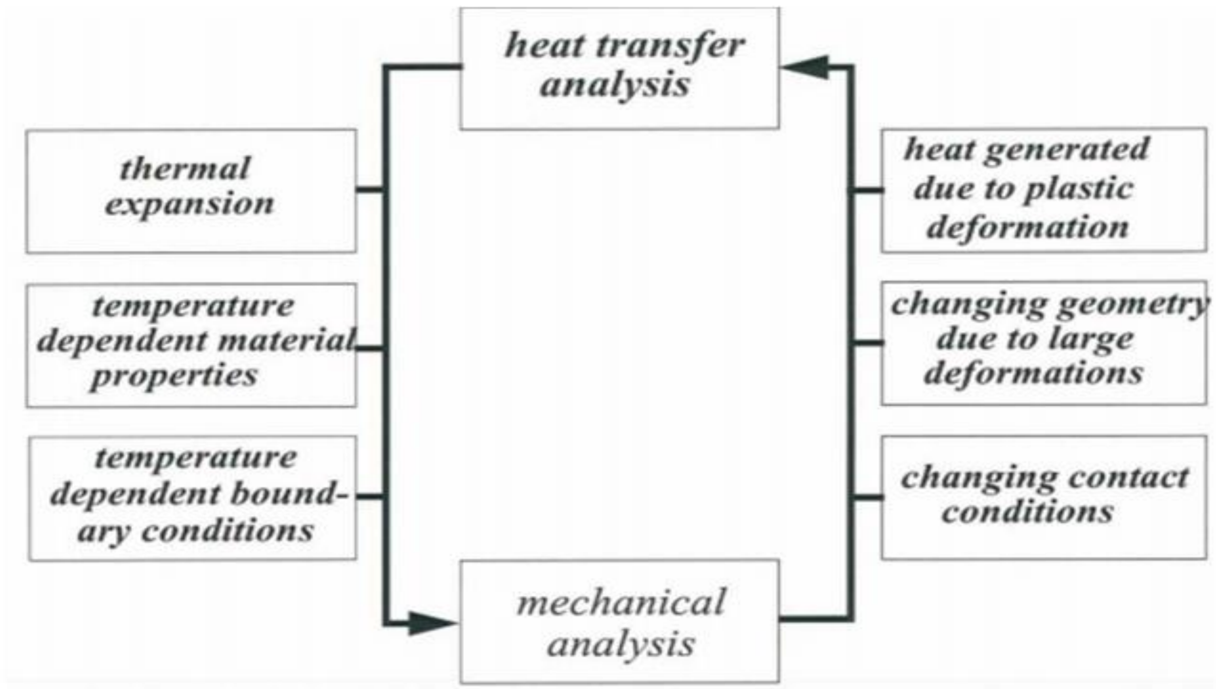


Figure4. 6 : Coupled Thermo-Mechanical Analysis.

To determine the heat generated from mechanical sources such as the work done by plastic deformation (volumetric heat generation) or friction heating (surface heat generation), it is necessary to specify how much mechanical energy is converted into thermal energy. This is done by means of the heat generation factor η that takes values between 0 and 1. Work by Warren & Taylor suggests that for metal plasticity a value of $\eta = 0.9$ is appropriate. In particular, the heat rate generated due to plastic deformation is determined by

$$\dot{q} = \eta\overline{\sigma}_{ij}\dot{\overline{\varepsilon}}_{ij}^{\ p}\ (W/m^3) \tag{4.58}$$

Where η = heat generation efficiency (fraction of the plastic strain energy that is converted to heat~0.9) 0< $\eta < 1$, $\overline{\sigma}_{ij}$= components of equivalent stress tensor (MPa), $\dot{\overline{\varepsilon}}_{ij}^{\ p}$= components of equivalent plastic strain rate tensor (s^{-1}).The heat transfer rate due to friction is expressed by

$$q^{"}_{fr} = \sigma_{fr}.v_r\,\xi \;\; \left({}^{W}/_{m^2}\right) \tag{4.59}$$

Where σ_{fr}=friction stress (MPa), v_r =relative sliding velocity between the roll and the work piece (m/s), ξ= fraction of friction energy that is converted to heat, $0 < \xi < 1$.In order to handle a coupled thermo plastic deformation problem, it is necessary to solve simultaneously the material-flow problem for a given temperature distribution and the heat transfer equations. The equations for the flow analysis and the temperature calculation are strongly coupled, making a simultaneous solution of their finite element counterparts necessary. Considering $T_{t+\Delta t}$ as a primary dependent variable, we have from Equation (4.56), with t=0 initially,

$$\dot{T}_{\Delta t} = \frac{T_{\Delta t}}{\beta \Delta t} - \frac{T_0}{\beta \Delta t} - \left(\frac{1-\beta}{\beta}\right)\dot{T}_0 = \frac{T_{\Delta t}}{\beta \Delta t} + \hat{\dot{T}} \tag{4.60}$$

Where $\hat{\dot{T}} = -\frac{T_0}{\beta \Delta t} - \left(\frac{1-\beta}{\beta}\right)\dot{T}_0$ Substituting equation (4.56) into equation (4.48) $C\dot{T} + K_c T = Q, yields,$

$$\left(K_c + \frac{C}{\beta \Delta t}\right) T_{\Delta t} - C\hat{\dot{T}} \tag{4.61}$$

The coupling procedure makes use of Equation (4.61) through the following sequence:(a) Assume the initial temperature field T_0,(b) Calculate the initial velocity field v corresponding to the temperature field T_0,(c) Calculate the initial temperature-rate field T_0 from Equation (4.54) using values from a) and b), (d) Calculate the quantity $\hat{\dot{T}}$,(e) Update the nodal point positions and the effective strain of elements for the next step,(f) Use the velocity field at the previous step to calculate the first approximate temperature T such as

$$\left(K_c + \frac{C}{\beta \Delta t}\right) {T_{\Delta t}}^{(1)} = {T_{\Delta t}}^{(1)} - {Q_{\Delta t}}^{(1)} - C\hat{\dot{T}} \text{ for } \hat{\dot{T}} \tag{4.62}$$

(g) Calculate a new velocity field with the solution of f), (h) Use the new velocity field to calculate the second temperature field such as

$$\left(K_c + \frac{C}{\beta \Delta t}\right) {T_{\Delta t}}^{(2)} = {Q_{\Delta t}}^{(2)} - C\hat{\dot{T}}\; for\; {T_{\Delta t}}^{(2)} \tag{4.63}$$

(i) Repeat steps g) and h) until both have converged, (j) Calculate the new temperature rate field $\dot{T}_{\Delta t}$, (k) Repeat steps e) through (j) until the desired deformation state is reached. The iteration process for temperature calculations is not likely to require much computing time, because only the heat input vector Q is changed during iterations and, as a result triangularization of the matrix is necessary only once. Moreover, additional iterations necessary to obtain a velocity field after a new temperature field is obtained should be relatively few, because the velocity field does not show much sensitivity to small variations of the temperature field [19].The model just described can be used to calculate the temperature distribution as well as the velocity, strain rate, strain and stress fields in the deformation zone during hot rolling. Plane strain state is assumed in the velocity field and four node quadrilateral elements are used in the non-linear finite element model.

4.1.8 FEA with different material modeling techniques

Generally speaking, finite element analysis simulation of the metal forming process is a non-linear problem**.** Nonlinearities may arise in the thermal problem due to convection, radiation, and temperature-dependant thermal conductivity and specific heat while mechanical problem may involve geometric and material nonlinearities and Contact is another source of nonlinearity. If contact occurs between deformable and rigid bodies in the mechanical problem, boundary conditions of the thermal problems are updated to reflect the new contact conditions[65]**.**Metal forming simulation is often classified as a class of highly nonlinear continuum mechanics problems because it is accompanied by large deformation (geometric nonlinearity), nonlinear materials behavior (material nonlinearity in both deformation and temperature),and frictional contact (nonlinear boundary condition) [41].In nonlinear finite element analysis, lower-order elements are often preferred over higher-order ones because of their robustness and reasonable accuracy at reduced costs. The software employs linear elements, rather than quadratic or cubic elements, to process nonlinearity. Nonlinear analysis is usually more complex and expensive than linear analysis. Also, a nonlinear problem can never be formulated as a set of linear equations. In general, the solutions of nonlinear problems always require incremental solution schemes and sometimes require iterations (or recycles) within each load/time increment to ensure that equilibrium is satisfied at the end of each step. Superposition cannot be applied in nonlinear problems. The iterative procedures supported in Marc are: Newton - Raphson, Modified Newton-Raphson, Newton-Raphson with strain correction, and direct substitution. If the R-P flow contribution model is chosen, a direction substitution is used. A nonlinear problem does not always have a unique solution. Sometimes a nonlinear problem does not have any solution, although the problem can seem to be defined correctly. Nonlinear analysis requires good judgment and uses considerable computing time[46]. The finite element method can be used for nonlinear, as well as linear, problems. Early development of nonlinear finite element technology was mostly influenced by the nuclear and aerospace industries. In the nuclear industry, nonlinearities are mainly due to the nonlinear, high-temperature behavior of materials. Nonlinearities in the aerospace industry are mainly geometric in nature and range from simple linear buckling to complicated post-bifurcation behavior. Nonlinear finite element techniques have become popular in metal forming manufacturing processes, fluid-solid interaction, and fluid flow. A problem is nonlinear if the force-displacement relationship depends on the current state (that is, current displacement, force, and stress-strain relations).General, rolling simulation sophisticated issue because all of the sources of nonlinearity exist in this problem. There are three sources of nonlinearity: The work piece contact with the roller (nonlinear boundary conditions), the work piece undergoes large deformation (nonlinear geometry) and the work piece has plastic deformation (Nonlinear material behavior).

4.1.9 Geometric Nonlinearities (GNL) (kinematic)

Geometric nonlinearity leads to two types of phenomena: change in structural behavior and loss of structural stability in the hot rolling due to the existence of large strains and deformations. There are two natural classes of large deformation problems: The large displacement**,** small strain problem and the large displacement, large strain problem. For the large displacement, small strain problem, changes in the stress-strain law can be neglected, but the contributions from the nonlinear terms in the strain displacement relations cannot be neglected. The large displacement, large strain problem, the constitutive relation must be defined in the correct frame of reference and is transformed from this frame of reference to the one in which the equilibrium equations are written. The kinematics of deformation can be described by the following approaches: Lagrangian Formulation, Eulerian Formulation, Arbitrary Eulerian-Lagrangian (AEL) Formulation. Finite element method is the most preferred technique, as it can easily include non-homogeneity of deformation, process dependent material properties and different friction models. Lagrangian Formulation: - Lagrangian formulation represents a more natural and effective approach than an eulerian approach for metal forming [99].The finite element mesh is attached to the material and moves through space along with the material. In this case, there is no difficulty in establishing stress or strain histories at a particular material point and the treatment of free surfaces is natural and straightforward. The lagrangian approach also naturally describes the deformation of structural elements; that is, shells and beams, and transient problems, such as the indentation problem. This method can also analyze steady-state processes such as extrusion and rolling. Shortcomings of the lagrangian method are that flow problems are difficult to model and that the mesh distortion is as severe as the deformation of the object. The lagrangian approach can be classified in two categories: The total lagrangian method and the updated lagrangian method. In the total lagrangian approach everything is referred to the original undeformed geometry, which is used as a reference. This approach is therefore applicable to problems exhibiting large deflections and large rotations (but with small strains), such as thermal stress, creep, and rubber analysis where large elastic strains are also possible. In the updated lagrangian method, the current configuration acts as the reference state and the mesh coordinates are updated after each increment. This method is good for problems featuring large inelastic strains such as metal forming and other problems where inelastic behavior such as plasticity causes the large deformations. Thus, this is the approach used for our rolling model. Eulerian formulation:-In analysis of fluid flow processes, the lagrangian approach results in highly distorted meshes since the mesh convects with the material. Hence, an alternative formulation, namely eulerian, is used to describe the motion of the body. In this method, the finite element mesh is fixed in space and the material flows through the mesh. This approach is particularly suitable for the analysis of steady-state processes, such as the steady-state extrusion or rolling processes[99].Arbitrary eulerian-lagrangian (AEL) Formulation: - In the AEL formulation referential system, the grid moves independently from the material, yet in a way that is spans the material at any time. Due to its strong resemblance to the pure eularian formulation, AEL is also called Quasi-eularian formulation.

4.2.1 Boundary Nonlinearities (BNL)

There are three types of problems associated with nonlinear boundary conditions: contact, nonlinear support, and nonlinear loading. In the rolling problem, contact plays a major role as it creates one of the most severe nonlinearities in mechanics. It is therefore very important to have a good understanding of its underlying principles. Contact by nature, is a nonlinear boundary value problem. During contact, mechanical loads and sometimes heat are transmitted across the area of contact. If friction is present, shear forces are also transmitted. Contact problems are commonly encountered in physical and manufacturing systems. In the rolling problem the contact problem occurs at the interface between the metal work piece and the rolls [89].Contact problems are characterized by two important phenomena: gap opening /closing and friction. The gap describes the contact (gap closed) and separation (gap open) conditions of two objects (structures). Friction influences the interface relations of the objects after they are in contact. The gap condition is dependent on the movement (displacement) of the objects, and friction is dependent on the contact force as well as the coefficient of (Coulomb) friction at contact surfaces. The analysis involving gap and friction must be carried out incrementally. Iterations can also be required in each (load/time) increment to stabilize the gap-friction behavior.

4.2.2 Material Nonlinearities (MNL) (physical)

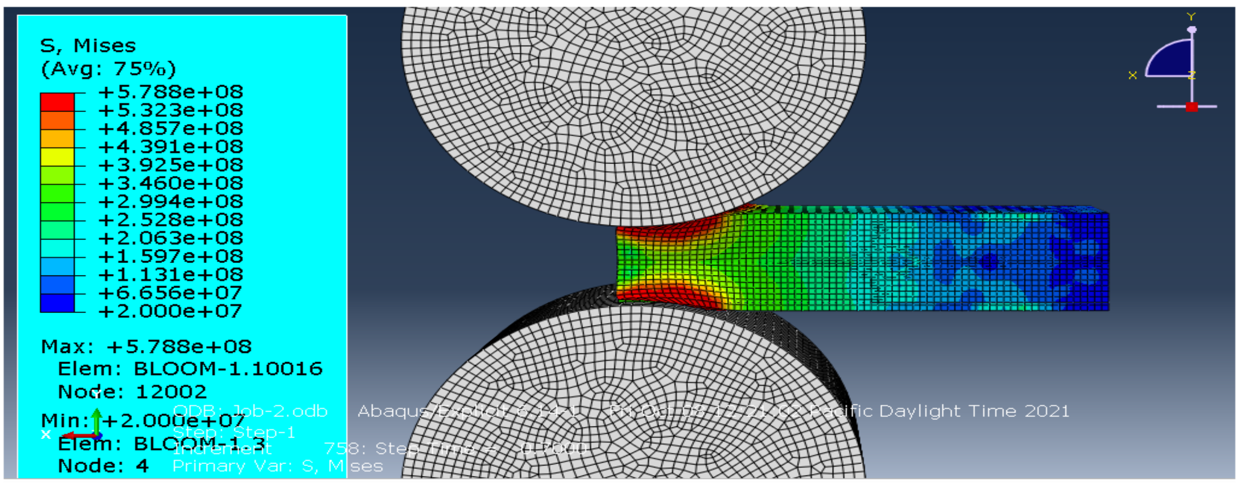
A solution requiring a nonlinear material model is probably the most difficult type of nonlinear problem. The degree of difficulty is proportional to the degree of nonlinearity. A nonlinear elastic problem is easier to solve than a moderately plastic problem. Even the latter is easier to complete than a model with significant plasticity and relaxation. This is the reason why the cold rolling problem is easier from the material modeling point of view, than the hot rolling problem. The success and efficiency of a nonlinear material solution are dependent on the choice of material model. Even the most complex material models are still significant idealizations of the real situation. The material non-linearities in the hot rolling problems are due to the high degree of plasticity of the rolling stock. In order to properly define the plastic behavior of the stock we have to define the following :(a) Yield Criteria: when plastic behavior is expected, we must tell the solver which criteria to seek to initiate yielding. Yield criteria are a function of the stresses in the model. Both the hot and cold rolling models in this thesis use the von Mises yield criterion which is considered the best criterion for ductile metals. (b) Hardening Rule: determines how the material model responds to repeated stress reversals, or switching between tension and compression. In ductile material that has never experienced plasticity; the yield point in tension can be expected to be equal to the opposite of the yield stress in compression.

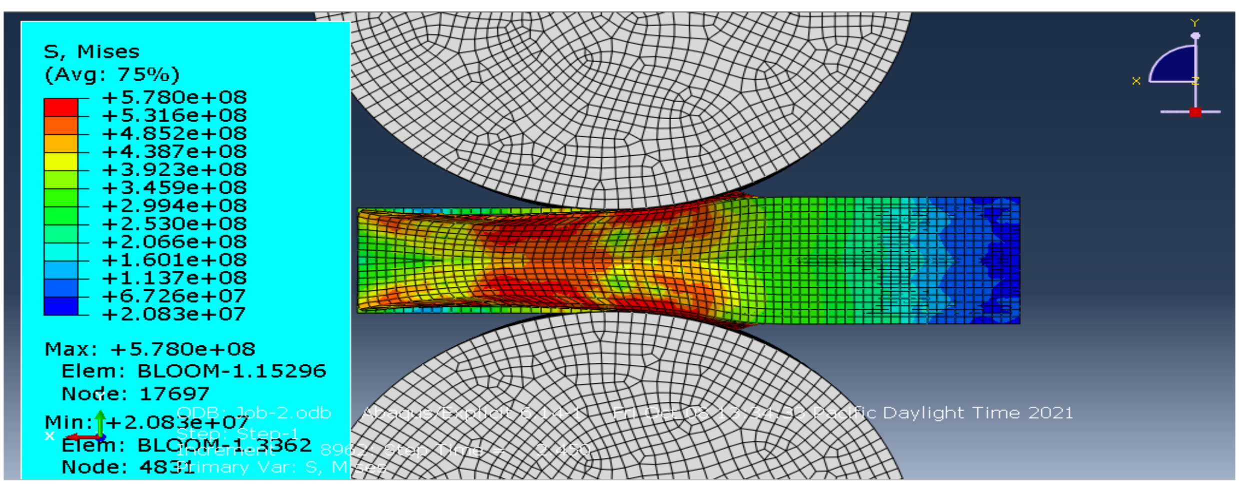
However, once the yielding has occurred, some materials experience a phenomenon known as the Bauschinger Effect, which causes the yield point in compression to be somewhat less than the compressive equivalent of the initial yield stress. Consequently, nonlinear solutions have implemented hardening rules to allow for adjustment of the yield point in stress reversals. An Isotropic hardening model does not take the Bauschinger effect into account and the compressive yield always equals the tensile yield; the absolute value of both equals the initially defined yield stress. A kinematic hardening model will take into account the reduction in the compressive yield point after a stress reversal. A kinematic model is more computationally intensive and should not be used unless a portion of the model is expected to yield in tension and then in compression. Most materials do experience strain hardening and will see an improvement in accuracy if the kinematic hardening model is used when needed. It is the case of the cold rolling problem which we modeled using the Ramberg-Osgood hardening material model. This was the rule used in the FEM models that will be described in the following chapters. (c) Flow rule: establishes the incremental stress-strain relations for plastic material. The flow rule describes differential changes in the plastic strain components dε pas a function of the current stress state. The Levy-Mises was used for the hot rolling case. Another important decision that had to be made for the nonlinear material analysis of the hot rolling problems was which material model to use. As we saw in the plastic material model takes into account the path dependent behavior that the material follows as it is hot rolled, the work piece enters and exits the roll gap and a plastic deformation as the work piece undergoes the bulk of the deformation process.

CHAPTER 5

Analysis, Result and Discussion

Rolling is the process of reducing the thickness or changing the cross-section of a work piece by compressive forces applied through a set of two rolls that revolve in opposite directions, while the space between the rolls being less than the thickness of the entering material and material passed between rolls is plastically deformed. The rolling process is analyzed in terms of the effect of rolling variables and parameters on the work piece and on each other during the process. Hot rolling is a (field variables coupling) and or coupled thermo-mechanical problem, where the material properties strongly depend both on them. Or the coupling between the thermal and mechanical problems takes place through the temperature-dependent material properties in the mechanical (stress) problem and the internal heat generation in the mechanical problem caused by plastic work, which serves as input for the heat transfer problem. The thermal analysis is generally transient analysis with temperature-dependent thermal properties and time/temperature-dependent boundary conditions. Thermo-mechanical modeling of the mild steel bloom and the roller was performed for hot rolling operations on low-carbon steel. The combination of both finite element method and thermo-mechanical process during rolling provides a methodology with a systematic approach to predict the behavior of the rolled material and analysis the effect of different variables and parameters. By considering different rolling parameters such as initial bloom temperature and rolling speed, the influence of these variables was studied on the behavior of the hot rolling process as well. In the first stage, stress and strain distribution within the deformation zone of the rolled bloom was obtained. 3D finite element models of single-pass hot rolling processes are developed with a simple geometry cross-section. Simulations are carried out with the commercial software ABAQUS.This software is a sophisticated simulation tool which considers the stress state with dedicated meshing and remeshing techniques for metal forming processes. To achieve the required precision in the simulations an adequately fine mesh is required, which must be carried out due to the three-dimensional stress state with full 3D elements. Due to the large plastic deformations the simulation mesh requires continuous remeshing to prevent the simulation from failing due to extremely distorted elements. Thermo-mechanical boundary conditions and material model flow curves are implemented based on assumptions described in the previous sections. Process parameters at each deformation stand are defined from real plant data: bloom cross-section geometry, work piece temperature, rolling velocity, rolling mill set-up equipment either horizontal. The developed nonlinear 3D finite element models are demonstrated to accurately analyze the metal flow behavior of hot rolling under a series of different parameters. Finite element method is proposed as a viable approach for the prediction of these parameters in such complicated thermo-mechanical problems. For instance, stress distribution within the deformation zone for the bloom is given in the fig below.





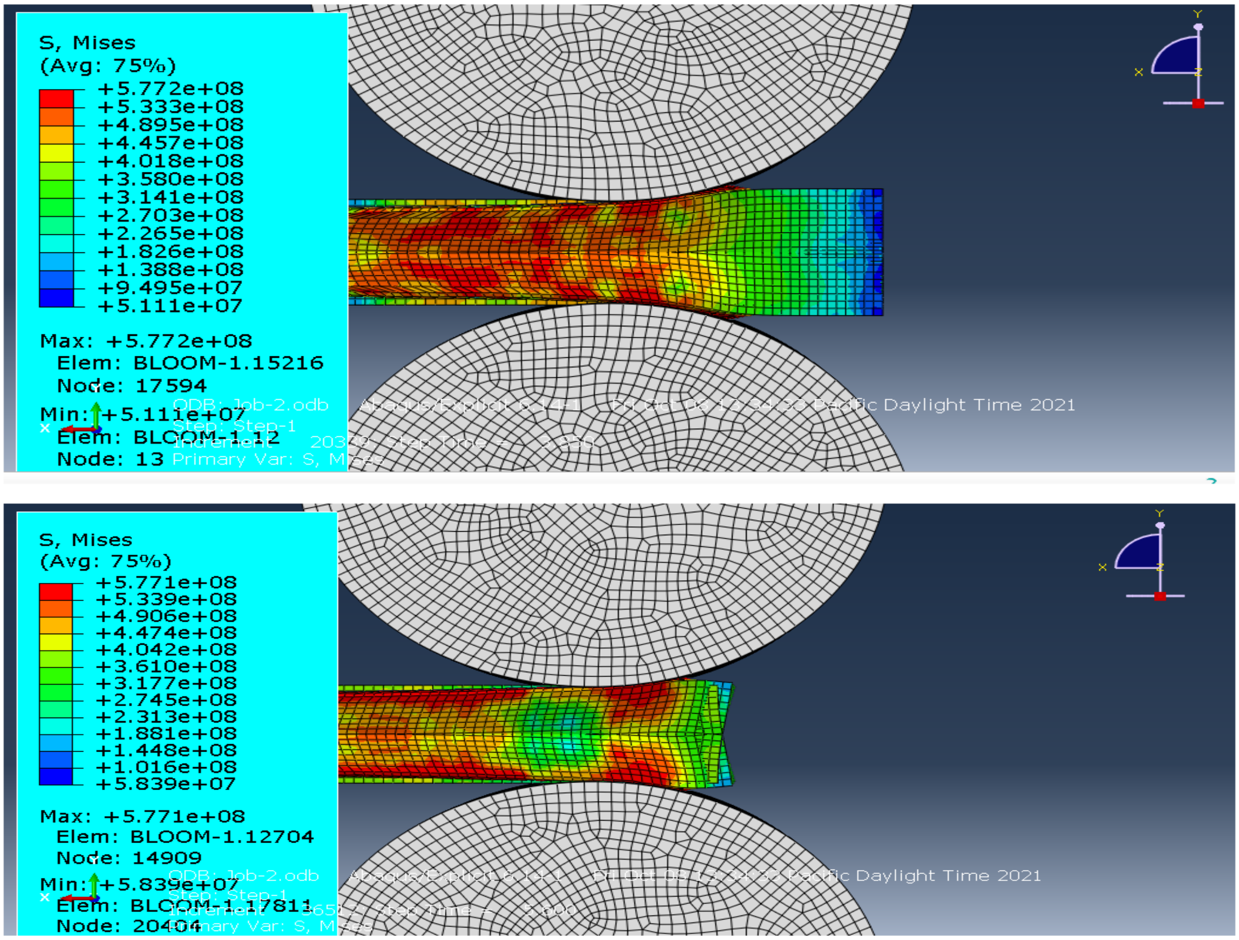


Figure5. 1 : Stress distribution within the deformation zone at different place when the work piece moving between the two high stand roller.

To demonstrate the stress and strain history on the surface and on center line of the rolled work piece, stress and strain variation curves along the rolling direction were computed and compared with published data. The properties of a hot rolled material are dependent on the evolved structure; it is a function of the restoration processes taking place during the hot deformation which are in turn dependent on the structural parameters of the hot rolling process (temperature, stress strain).The operations performed in the metal forming (hot rolling) can require a coupled thermo-mechanical analysis and the following conditions pertain or physical phenomena must be modeled and observed: The body undergoes large deformations such that there is a change in the boundary conditions associated with the heat transfer problem and Deformation converts mechanical work into heat through an irreversible process which is large relative to other heat sources. The interaction between the mechanical and thermal field can be solved within one time step leading to simultaneous solutions. A coupled thermo-mechanical simulation model was developed using the commercial finite element code ABAQUS. The rolling model is 3D, thermo-mechanical, transient and nonlinear.ABAQUS/CAE is divided into modules, where each module defines an aspect of the modeling process; for example, defining the geometry, defining material properties, and generating a mesh. As you move from module to module, each module contributes keywords, parameters, and data to form an input file that you submit to the ABAQUS/Explicit solver for analysis. The finite element model currently used in this work is based on lagrangian and transient. Though these models yield results that are generally depend on the geometrical data. For example, you use the Property module to define material and section properties and the step module to choose an analysis procedure; the ABAQUS/CAE postprocessor is called the visualization module. Knowledge of the stress-strain curve is needed for efficient processing, along with the mechanical property and Models must be developed, based on equations that relate the deformation parameters. Without the knowledge of the influences of variables such as ,material properties, and work piece geometry on the process mechanics of rolling, it would not be possible to predict effects of parameters(geometrical parameters, process parameters, material parameters) which plays a major role in plastic deformation and prevent the occurrence of defects. This evaluation was made by studying the von Mises stress and the plastic strain in the bloom. The goal of the present study was to provide models that describe the stress-strain curves of ASTM A36 mild steel bloom under hot-rolling conditions and to provide data as input to the numerical tools, such as finite-element method, for detailed calculations of stress, strain, and related properties. The focus had been on modeling the stress-strain behavior as functions of temperature, strain rate. In general there are no standard test procedures for determining flow stress curves at the relatively high temperature and strain rate conditions encountered in industrial processing and metalworking (hot rolling).

The variables stress and strain describe the distribution of forces that affect not only roll life, but also the general operation of the mill and quality of the rolled product. The basic instrument (quantities) a function of the geometry of the work piece that may be used to describe the mechanics of plastic deformation of the metal when a metal deforms from one shape to another under an external load and result such as stress, strain which can predict easily properties of the materials.

5.1 Temperature evolution

It is generally accepted that, in hot deformation processes, temperature is the most significant parameter for the determination of product properties. The fundamental parameter in metal forming especially under hot rolling processes is the temperature. It is accepted that, in hot deformation processes, for the determination of product properties because large number of material properties vary with temperatures. In hot rolling the chief factors influencing the yield stress are; the type of material, the amount and rate of deformation and the temperature. An increase of the initial bloom temperature and thickness will reduce the rolling force. As can be seen the thermal properties required to solve the thermal problem are: material density, specific heat and thermal conductivity, all of which are temperature dependent. It would be necessary to know the values of these properties in function of the temperature in order to perform a thorough analysis. The mechanical properties required to simulate the mechanical problem are related to the material behavioral model used, for this study is a thermo-plastic model with von Mises yield criterion and the modulus of elasticity, the Poisson coefficient, the yield stress, the tangent modulus and the coefficient of thermal expansion are required because all of these properties are also temperature dependent. Ductility, strength, texture etc. are each significantly influenced by the temperature. Ductility increases and yield strength decreases when work temperature is raised. Any deformation operation can be accomplished with lower forces and power at elevated temperature. Temperature variation during hot rolling is caused by the combined effect of two factors. One is the heat generated by the friction between the rolls and metal surface and plastic deformation of the metal (work piece) and the heat loss to the rolls through conduction and temperature changes continuously as a result of heat losses to the surroundings by convection and radiation. At high temperatures rolling, recrystallization eliminates the effects of strain hardening so there is no considerable increase in strength and hardness or decrease in ductility. Over 90% of the energy imparted to a deforming work piece is converted into heat and it may increase the temperature of the metal if deformation rate is high. Heat is lost through the work piece surfaces after the deformation, with the majority of cooling occurring at contact points between the metal and the lower temperature tooling. The success of a hot deformation process depends on the ability to control the temperatures within the deformed metal. A change in the temperature distribution contributes to the deformation of the body through thermal strains and influences the material properties. The temperature rise of the work piece during hot rolling can be attributed to various factors such as rolling speed, initial temperature of the bloom, plastic deformation of the work piece, the cross sectional shape of the work piece during the rolling operation. As known above the rolling process achieved at temperature 1100C, the temperature distribution around the work piece with maximum value 1200 C for the square bloom mild steel. In the roll-gap the heat is transferred from the bloom to the roller. The bloom and roller temperature in the roll-gap region are effectively coupled through the heat transfer coefficient at their interface. The simultaneous solution of the governing equations of heat conduction for the bloom and the roller has to be carried out. In the present study it was assumed that axial conduction in the work roll is negligible. Heat transfer from the roll occurs by convection to atmosphere along its circumference except in the roll-gap region where it receives heat from the rolled material or work piece. The temperature gradient between the entrance and exit of the horizontal rolling stand is not uniform.

5.2 The temperature influence

A finite element model has been developed which takes into account the heat transfer phenomena of the contact region and the combined thermo-mechanical heat transfer. Apart from very specific metal-forming conditions where the process is very slow and may be considered as thermal analysis, the temperature distribution plays an important role, and the plastic deformation potential must be temperature dependent. Large number of material properties varies with temperatures. The temperature affects substantially the mechanical properties of mild steel because it is critical parameters for determining the material properties of the heated metal to deform. In general, temperature has a potential that influence metal heating which is explained by the increase of amplitude of atoms' thermal oscillation, which causes the weakening of their ties and facilitates the process of plastic deformation. Besides that the rate of recrystallization process increases at higher temperatures and contributes to the metal softening. The resistance to deformation decreases due to increasing of metal heating temperature within the range of temperatures of hot rolling of metal forming, and the plasticity increases. The distinction in resistance to deformation between the steels with different carbon content becomes insignificant at high working temperatures (more than 1100ºC).The resistance to deformation is increasing due to the development of the process of strengthening with the increase of deformation degree. The period of deformation is reduced with increase of the rate of deformation. The increase of the bloom width during the rolling is called broadening or lateral deformation. Temperature of bloom (stock) during the hot rolling process varies from rotation pass to another due to following mechanisms: Heat Generation due to plastic deformation. Heat is generated in the stock when plastic deformation of the stock takes place as a part of the energy expended to deform the stock is converted into heat and Heat Transfer. Heat transfer mechanisms include conduction (between roll and stock), convection (between stock and environment), and radiation (between stock and environment). Analysis of the flow stress behavior and the effect of process parameters on the deformation process and overall effect on the hot rolling process. The flow curves generated from the single pass hot rolling using two high stand roller showed that an increase in stress with increase in strain and decrease in temperature when temperature and strain rate were kept constant in each deformation pass, respectively. As seen from the figure at any given temperature, the peak stress or flow stress was observed to increase with strain rate. Figure 34. Shows the variation of flow stress with strain in different processing temperature and it shows that the effect of temperature on the stress-strain curves. The flow curves show an increase in flow stress with strain rate for temperatures, though higher stresses were clearly attained when the deformation was carried out in the lower temperature. Figure 34 denotes the variation of von-Mises equivalent stress which is an important parameter in terms of understanding global stress state of material. Figure 30 as mentioned before, the stress distribution across the width of the bloom is non-uniform and lead to differences in material flow behavior. It is clearly shown that the highest compressive state of stress and the highest gradient of stresses occur near to the dog bone shape as a result of the significant thickness reductions suffered by this region of the bloom. When stress-strain behaviour is examined over a wide range of different hot working conditions, it is usual to report a number of curves as typical examples and characteristic values of the flow stress as functions of temperature and strain rate. In metal forming processes such as rolling the flow stress of the metal is a key factor for successful operation. The forming pressure and the load are directly related to the flow stress, and therefore a lower flow stress is desirable in most of the forming operations. Since the flow stress is usually reduced with temperature, a high working temperature is beneficial to carry out the operation with a low load or pressure. The flow curve describes the stress-strain relationship in the region in which metal forming takes place. It indicates the flow stress of the metal-the strength property that determines forces and power required to accomplish a particular forming operation. In hot deformation processes the metals sensitive to changes of temperature and strain rate (rate of deformation) and the influence of these parameters is much stronger than the influence of the strain.

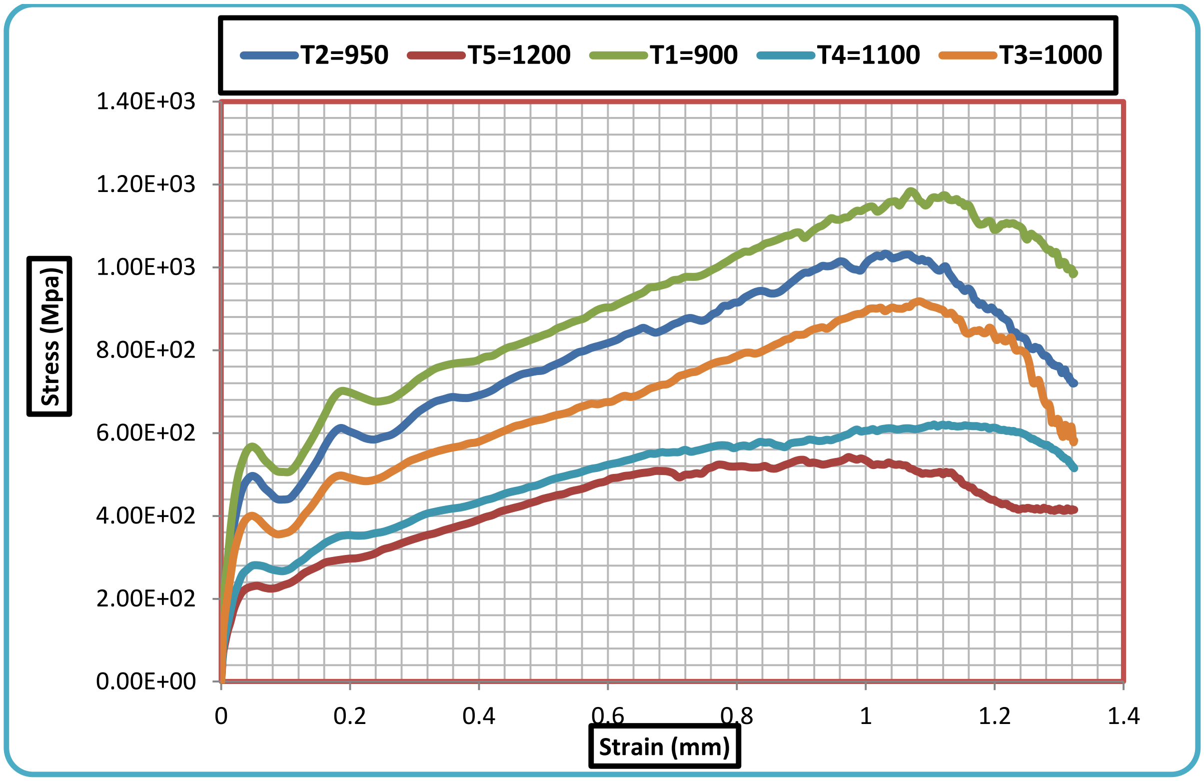


Figure5. 2: The coupled effect of temperature and strain on stress-strain curves for ASTM A36 mild steel for constant strain deformation but varying temperatures.

As expected, the flow stress at a given strain increases with decreasing temperature for a given bloom size and strain rate. Flow stress also depends on strain rate and temperature, usually increasing with strain rate and decreasing with temperature. During deformation, the stored energy of the material is raised by the presence of dislocations and boundaries. Simultaneously, because of the high temperature, dynamic recovery occurs. During recovery, rearrangement and annihilation of dislocations occurs which lowers the stored energy. Dynamic recovery and recrystallization are important processes because they lower the flow stress of the material enabling it to be deformed more easily. Dynamic recovery is the term used to describe the thermally activated recovery occurring during deformation at high temperature. In general the effect of temperature on flow stress can be explained by the fact that the two restoration mechanisms, dynamic recovery and dynamic recrystallization, are thermally activated. The rate of formation of cells or sub grains by dislocation rearrangement (recovery) as well as the rate of nucleation and growth of strain-free grains (recrystallization) increase with increasing temperature as a result of faster grain boundary mobility and diffusivity. Before hot rolling of microalloyed steels, the steels are soaked at high temperature to dissolve the particles to get enough microalloying elements in solution. At low temperatures the microalloying elements start to precipitate causing a retardation of recrystallization. For conventional controlled rolling the finishing passes are carried out below the temperature where the material recrystallizes. When no recrystallization occurs between passes, the strain is accumulated and the austenite grains become severely deformed. This provides for more preferential nucleation sites for ferrite during subsequent transformation and a fine ferrite grain size is obtained. The stress of the material will be a strong function of strain, strain rate, and temperature,

5.3 Model Predictions and Experimental Stress-Strain Curves

Every type of metal forming is characterized by the definite scheme of stresses and strains actions. The combining of stressed and strain states schemes in the specific process of metal forming is called mechanical scheme of deformation. The goal of this study was to provide models that estimated the stress-strain curves of mild steels under hot-rolling conditions. The thermo-mechanical models were used during hot rolling to provide data as input to the numerical tools, such as finite-element method, for detailed calculations of stress, strain, and related properties. The focus had been on modeling the stress-strain behavior as functions of temperature. Model predictions and experimental data result stress-strain a curve presents that the results of model predictions versus experimental data for each individual stress and strain value of mild steel. The ABAUQS modeling curve and experimental conditions as were observed from the given the graphs below typically the result presented that the agreement between the experimental data and the ABAQUS model predictions have fair approach. To describe the stress-strain curve mathematically, our initial choice was which fitted the elevated-temperature experimental data well for the stress-strain portion that was prior. The rigid-plastic model describes the flow stress behavior and incorporate yield stress at the start of the stress-strain curve so begins at the yield stress when strain is zero. The purpose of this work was to develop constitutive equations that predict the stress- strain curves of mild steels bloom as functions of processing variables, such as temperature. The results from the coupling between the pure mechanical model of the work piece and the thermo-mechanical model of numerical calculations are carried out based on a geometric relationship for the hot rolling stress distribution. This work proposes a simplified approach to tangential stresses for the rolling under hot milling for a number of parameters and variables. Stress distribution under hot rolling gap in a radial direction is computed by finite element model simulations and the result shows good agreement with experimental data[100].

Abaqus Result	Stress(Mpa)	380	420	435	447	460	485	500	530	545
	Strain(mm)	0	0.02	0.04	0.06	0.08	0.1	0.12	0.15	0.165
Experimental Result	Stress(Mpa)	100	150	200	300	400	500	600	700	800
	Strain(mm)	0	0.05	0.15	0.2	0.3	0.4	0.5	0.6	0.7

Table5. 1: Comparison of FEM methods and experimental data

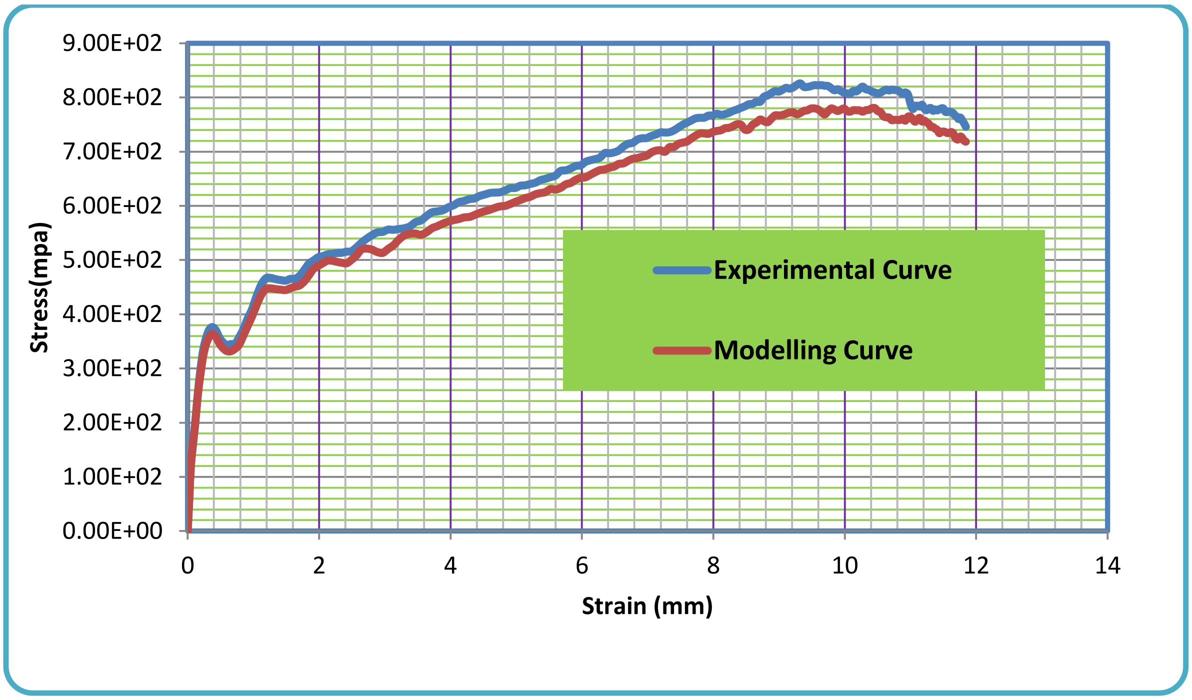


Figure5. 3: Result of model predictions vs. experimental data flow curves of the hot rolling.

All models look quite promising, since it avoids analyzing of the bloom in the general solution and enables to catch the relevant phenomena which are induced by compressive loads. Stress behavior on the bloom is also identified with all possibility of the loads, which were less attention given in different literature. In general, experimental validation for the thermo-mechanical coupled numeric model of finite element model is strictly needed to allow a suitable model improvement. However, the experimental setup is very complex, expensive and time-consuming, which are difficult to be completed on existing hot rolling milling, which is used daily in the metal forming industry/manufacturing (the final stage of metallurgical manufacturing) processes. Moreover, the work focuses on the modeling of hot rolling plastic deformation evolution with information from the beginning, by assuming that all plastic stresses can contribute to the deformation evolution for a given number of loads. Even though the results obtained are satisfactory for most of the models, there are limitations which can have negative effects on the utilization of the model or on its effective use for simulation.

5.4 Effect of temperature on stress

In the steel industry hot rolling is plays a major role especially in the deformation process in which the work piece subjected to the cyclic thermal and mechanical loading that explained in common as thermo-mechanical coupled and the detail deformation information, such as strain, stress, temperature, velocity and consider the complex interactions between strain, strain rate, temperature variation due to rolling force pressure imparted by roller contact (mechanical part) and non-uniform temperature distribution due to heat generation rate in the deforming work piece due to plastic deformation and heat loses and heat transfer between roller and work piece at the contact place and to the environment through the three types heat transfer mode radiation, convection and conduction (thermal part). Mostly hot rolling processes has been toward the prediction of temperature, strain and stress distributions in the rolled material, as these variables control the final microstructure, and mechanical properties of the rolled product. Due to thermal influences, developing the bloom temperatures drastically decrease the flow stress of bloom but decrease of rolling force. An accurate knowledge of temperature is essential for the accurate prediction of rolling parameters effect during the plastic deformation metal under hot rolling process. In order to obtain the stress distribution, simulations have been performed utilizing the plane assumption. The consideration of temperature effects in the analysis of metal forming problems is very important. At high plastic deformation can induce phase transformations and alterations in grain structure that in turn, can modify the flow stress of the work piece material as well as other mechanical properties. When a metal is deformed at room temperature, its resistance to further deformation increases (strain hardening).So work hardening (strain hardening) resulting from deformation below the recrystallization stop temperature, which causes pan caking of the grain is to be considered. Strain hardening, also called work hardening or cold working, increases the yield stress depending on the accumulated strain, or the strain path, of the material. Strain-rate hardening increases the materials' resistance to plastic deformation as deformation occurs more quickly making the yield stress a function of the plastic flow rate.

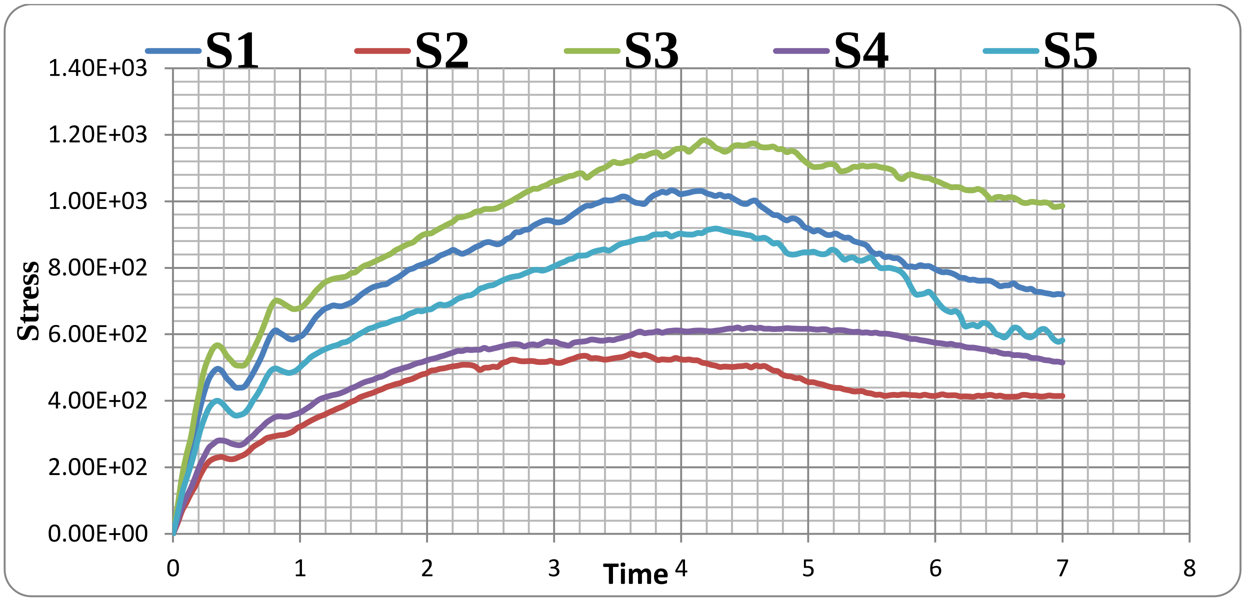


Figure5. 4: Variation of von-Mises equivalent stress at constant time with different temperature

The above graph indicates that stress at constant time but at different temperature input value. **S1**=stand for stress at temperature 950℃, **S2**= stand for stress at temperature 1200℃, **S3**= stand for stress at temperature900℃, **S4**= stand for stress at temperature1100℃,, **S5=** stand for stress at temperature 1000℃. From the above result we observed that as the temperature increases the stress value and stress graph become decreases.

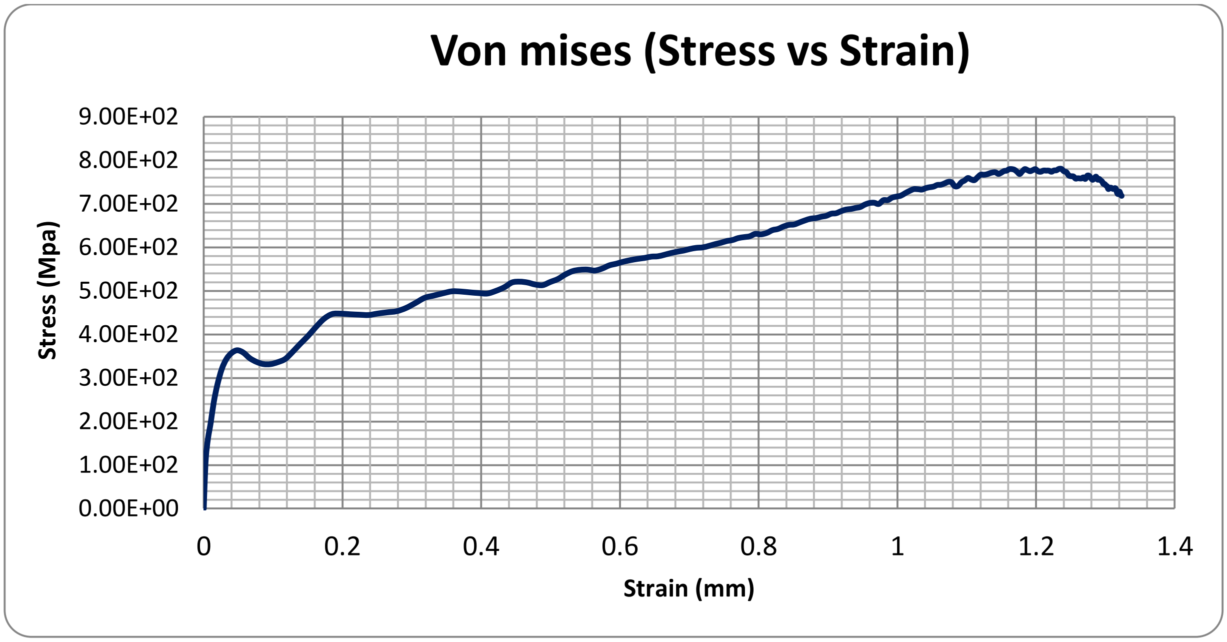
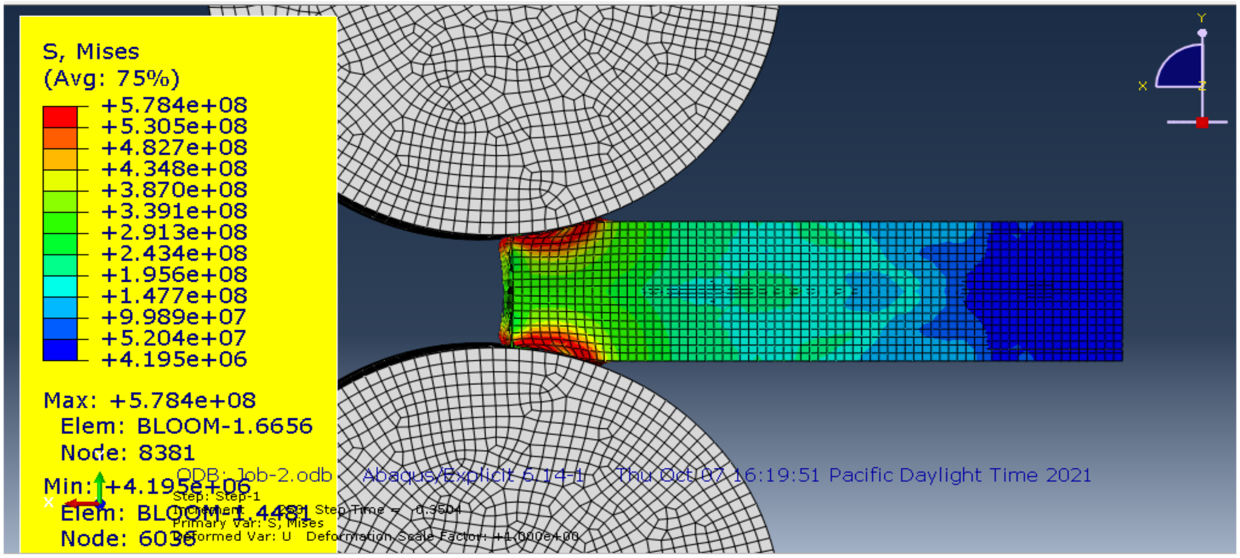


Figure5. 5 : Distribution of Von Mises stress vs. Time for single temperature.

It can be seen from figure 31, it is equal to **(5.784e08)** just after the bloom enters between the rollers and after some increment of rolling time, it increases gradually until reaches **(5.788e08)** then slightly decreases and oscillates about a certain value of about **(5.770e08)**.Thermal effect influences that, increasing or developing the bloom temperatures decrease the flow stress of bloom but decrease of rolling force. A finite element simulation was carried out using ABAQUS 6.14 software (Explicit) observed the influence of these parameters on the hot rolling process, equivalent plastic strain and stresses.



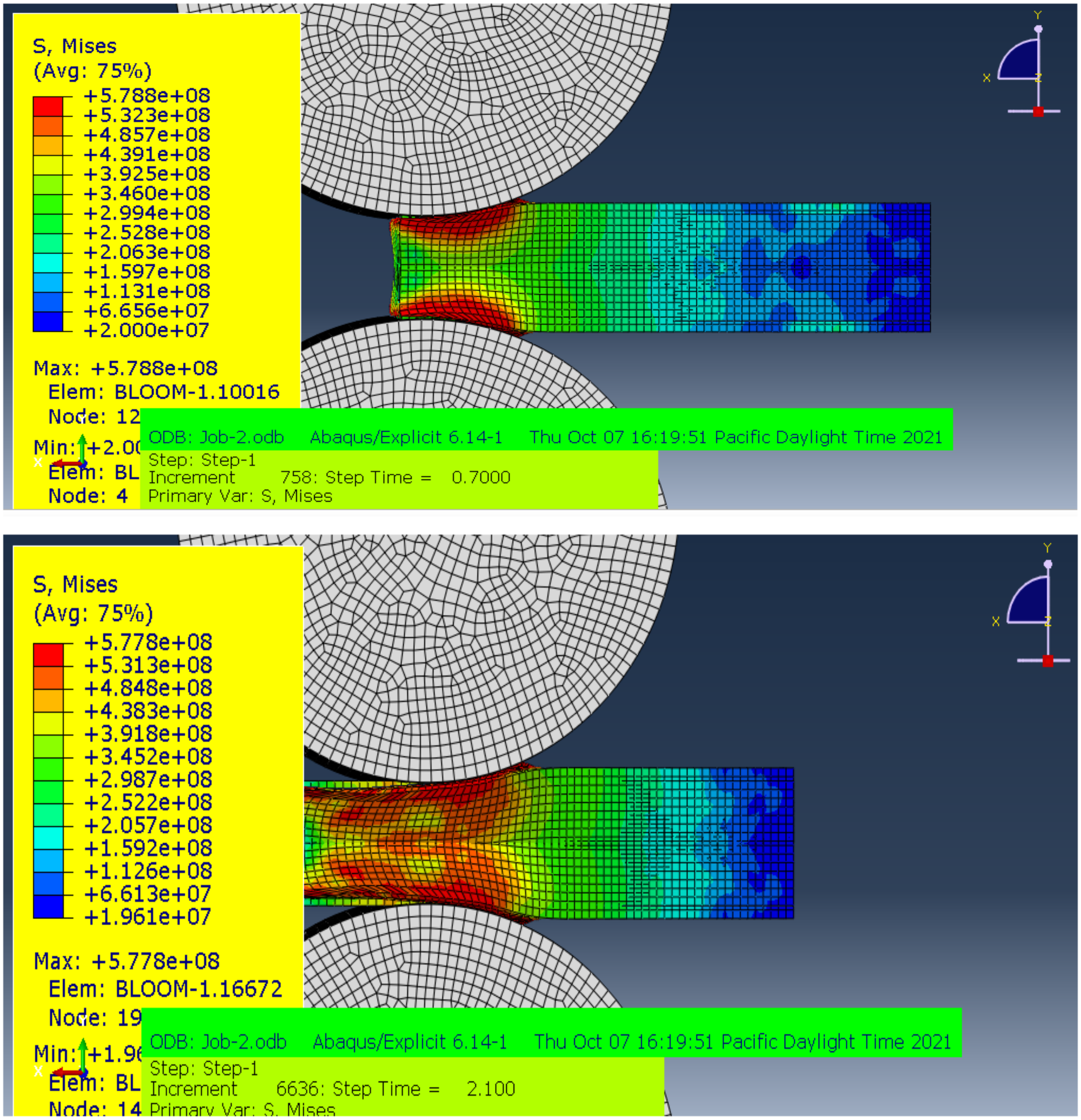


Figure5. 6 : Different stress values at different contact area of work piece.

This can be explained as; at beginning of the rolling process, the plastic deformation occurs until plastic strain reaches a certain values then when the material is hardening consequently the materials become more resistant to plastic deformation. The maximum stress is $5.778x10^8$Pa, for ASTM A36 mild steel bloom which is in agreement with the experiment value of structural low carbon steel S235JR.

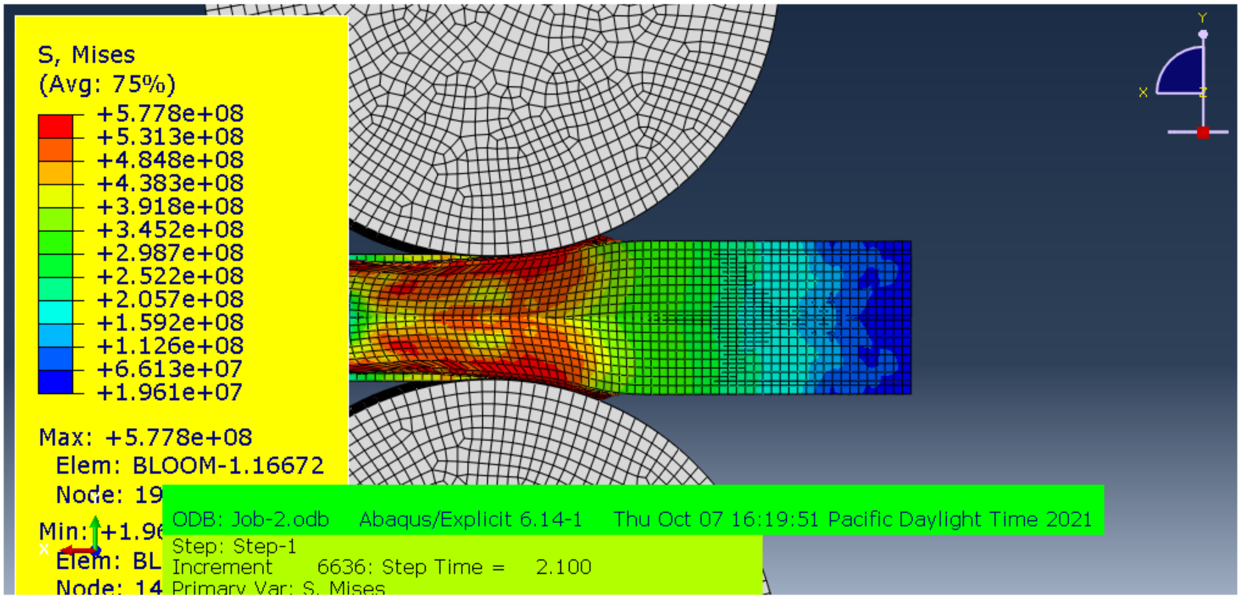


Figure5. 7 : Distribution of stress during rolling process for roller diameter; R= 460 mm, roller speed = 300 mm/sec and friction coefficient; μ = 0.3.

In general essential mild steel (bloom) properties that reflect more changes under the effect temperature are low yield strength and high ductility, this mean that ductility increases and yield strength decreases when the rolling temperature is raised. Near the ends of the bloom, the stress and strain is different due to the special conditions that occur during the start and finish of the rolling process. During the initial contact between the roll and the bloom, the contact length is small and the friction varies between adhesion and slip. After this, the process reaches a steady state until the end of the pass, at which the bloom and roll starts to lose contact, and the contact length once again changes.

5.5 Stress (Stress distribution)

At this stage, using the initial bloom temperature applied for the bloom mild steel the thermo-mechanical stresses distribution within the work piece or rolled material was first determined.

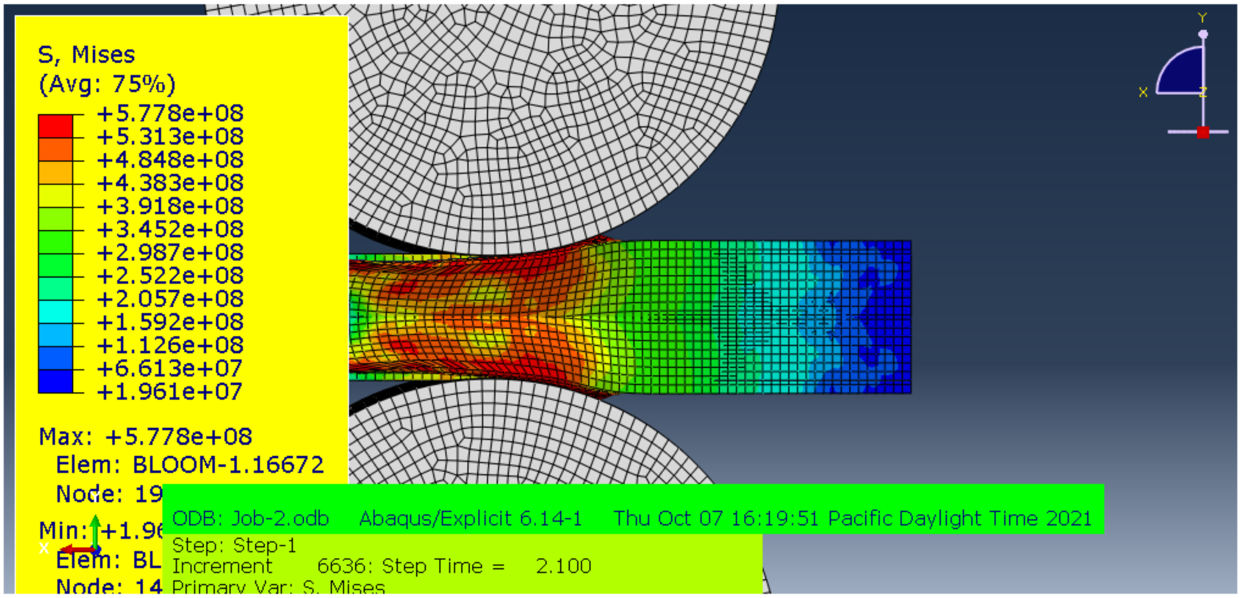


Figure5. 8 :Distribution of effective thermo-mechanical stress within work piece under initial temperature.

In general in hot rolling processes, the work piece is subjected to external and internal forces in order to achieve a certain desired shape. Under the action of these forces, the work piece undergoes displacements and deformation and develops internal forces. If the stress in the work piece is greater than the yield stress, the material no longer exhibits elastic behavior, and the stress-strain relationship becomes nonlinear. Stress is a measure of the intensity of internal forces generated in a body. In general, stresses in a body vary from point to point. As shown in the Figure 35 below stress rate is analyzed. Stress increases with decreasing temperature and time and increasing strain rate. The deformation of the work piece takes places in step by step reduction in height. The hot rolling can be easily done by heating the work piece for the required time and apply load. Figure 5.8 shows the stress distribution on the workpiece.

Thermal loading has a more influential effect on the stresses developed in rolling mills during high-temperature rolling operations; however, the influence of mechanical loading on the hot rolling mills should also be taken into account in order to a sound rolling schedule to operate.

As shown in the Fig 5.8 Stress rate is analyzed. The result indicates that as rate of deformation increase, stress development in the work piece also increase with load applied constantly. Stress increase as the time increase in the rolling process and once the stress arrive at certain point, there is longer stress increment development in the work piece. Stress depends fundamentally on the dislocation structure which depends chiefly on the “metallurgical history" of strain, strain rate, and temperature. The deformation processing situation is best viewed as a total system. The deformation zone is concerned with the distribution of stress, strain, and particle velocities, and with the overall pressure required performing the operation.

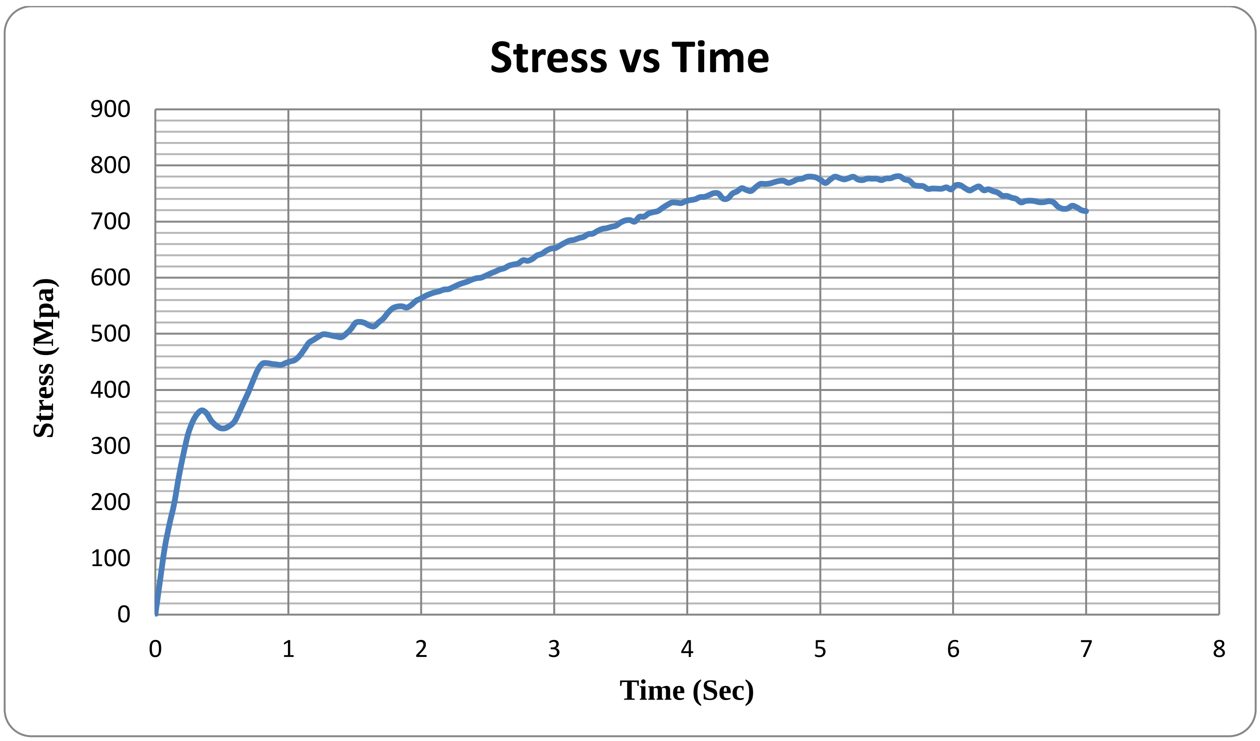


Figure5. 9 : Stress vs. time curve from FEM by ABAQUS Software.

The result on the graph indicates that the rate of deformation increases that means the stress development in the deformed work piece also increase with the load. As deformation increases, the deformation resistance increases due to increasing dislocation takes place within a particles of work piece content. In constitutive modeling, the flow stress is expressed as a function of other process parameters, such as strain, strain rate, and temperature, which describe the state of the plastic deformation in the deforming metal. Stress distribution is essential in the metal forming, which may contribute to increased production efficiency and product quality. Plastic material properties are dependent upon the rolling temperature and rolling speed, and thus can significantly influence the manufacturing process. At varying rolling speeds, the stress distribution were calculated and investigated. The flow stresses are dependent on rolling speed and temperature. The stress difference is caused by temperature softening effect, under which stress is reduced at same deformation. The flow stress patterns indicate that stress is concentrated at higher rolling temperature can reduce internal stress. As the plastic deformation of the specimen increases, the metal becomes stronger (strain hardening). In hot rolling process according to the constitutive equation, the parameters affecting stress distribution in the deformation zone are strain, strain rate and temperature. The lowest temperature of the bloom occurs at the exit of the deformation zone because the position is in the contact with the roll for more time, which results in more heat loss. The maximum strain rate generally is produced in the entry position of the deformation zone because the deformation occurs in this zone suddenly. Large plastic deformations occur in the contact zone because the continuous deformation and flow of metal occurs along rolling direction. It is observed from Fig.5.10 that the maximum effective stress occurs under the roll at the contact zone. Temperature, strain and train rate have major effect on stress distribution and the effect of strain is dominant the effect of strain is dominant.

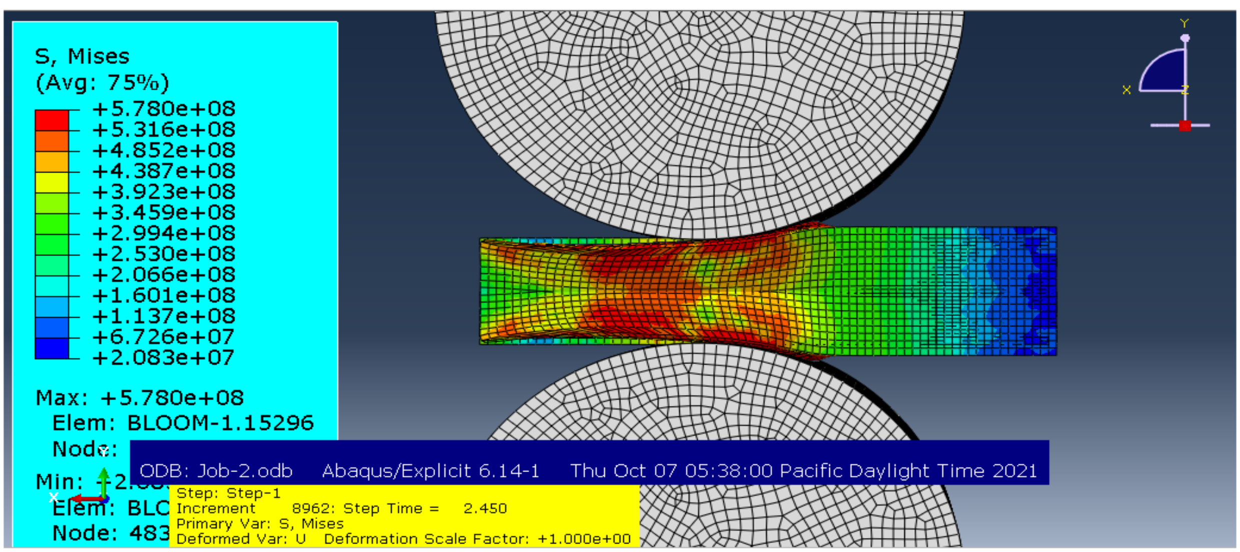


Figure5. 10 : Distribution of effective stress in the deformation zone.

Figure 5.10 show the contour plot of the effective stress, around the work piece during the rolling process. It can be seen that the maximum value of effective stresses was 57800 MPa reached. Under hot rolling Plastic strain, von Mises stress, decreases due to higher roll diameter while Contact pressure roller size increases more. The stress, strain & strain rate, the temperature in the roll and the bloom, are developed throughout a steady-state analysis of the process involved. During the duration in the rolling process, the plastic strain varies little over time in the high plastic strain region during the steady-state (rolling) phase of the simulation. Figure5.10 is the stress contour in the rolling direction of horizontal roller during the rolling process, which shows that the highest stress is located in the contact area of the work piece and roller during rolling.

5.6 Plastic strain and 3D Simulation Results

In order to better understand the deformation behavior in hot rolling of the strain development and final equivalent plastic strain in different regions of the bloom are investigated. The hot rolling sequence of the has been simulated to obtain the plastic strain across the cross-section after the hot rolling process takes place. Strain describes the amount of deformation in a body. If the stress in the work piece is below the yield stress of the material behaves elastically and the stress in the work piece is proportional to the strain. When a body is deformed, points in that body are displaced. Strain must be defined in such way that it excludes effects of rotation and translation. The strains on an object depend on the final state of stress and flow or increments of plastic strain are related to increments of plastic stress. Understanding plastic strain during hot rolling process is important to control microstructure evolution, quality of the product of the rolling process. In order to obtain the strain and stress distribution, simulations have been performed utilizing the plane strain assumption.

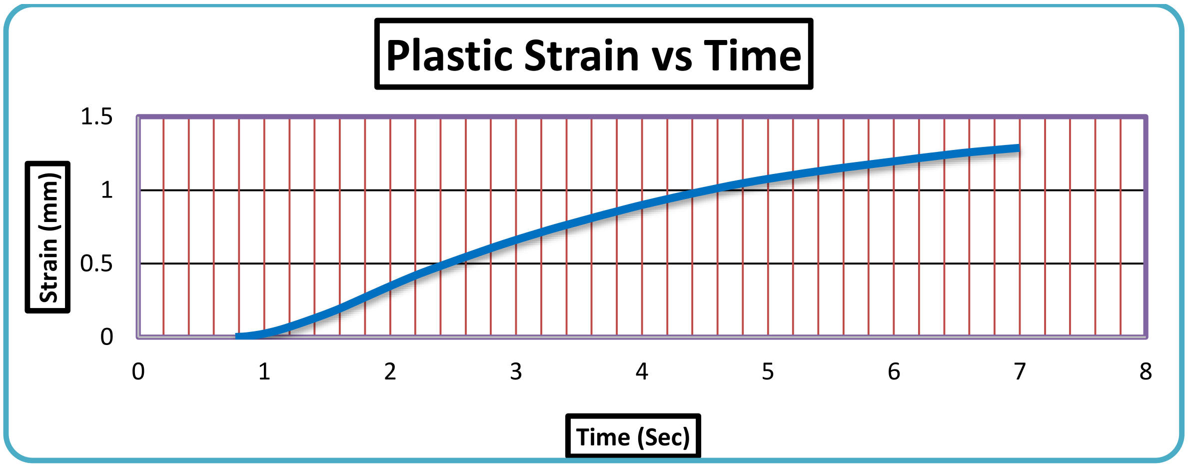


Figure5. 11: Schematically Representation of Equivalent plastic strain vs. Time

The final equivalent plastic strain values through the thickness of the bloom in different direction of coordinates. However, 3D simulation results show that there is plastic strain development in the bloom area. To explain this result, the plastic strain tensor histories in the 3D simulation directions of tensor components are presented. In 3D simulations, direction “1” is x-direction, “2” is the y-direction and “3” is z-direction. Due to the increase of reduction, the effective strain increases, the strain increases after the bloom moved between the rollers is shown in figure 5.12, 5.13, 5.14 and plastic strain distribution in specific direction.

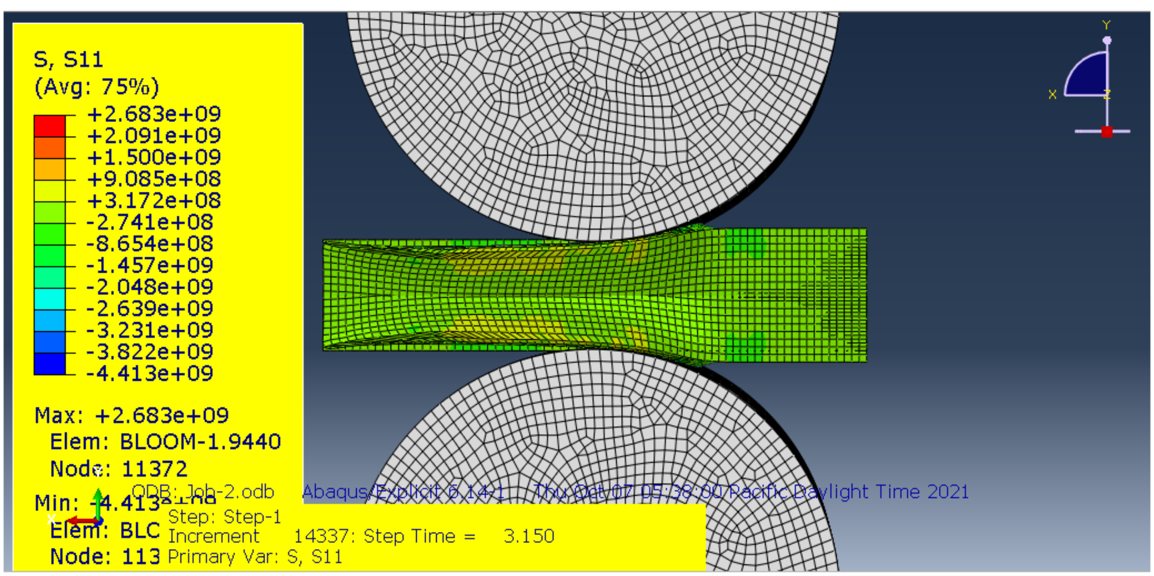


Figure5. 12: Plastic strain in x- direction with the maximum and minimum value of node number and max and min strain value.

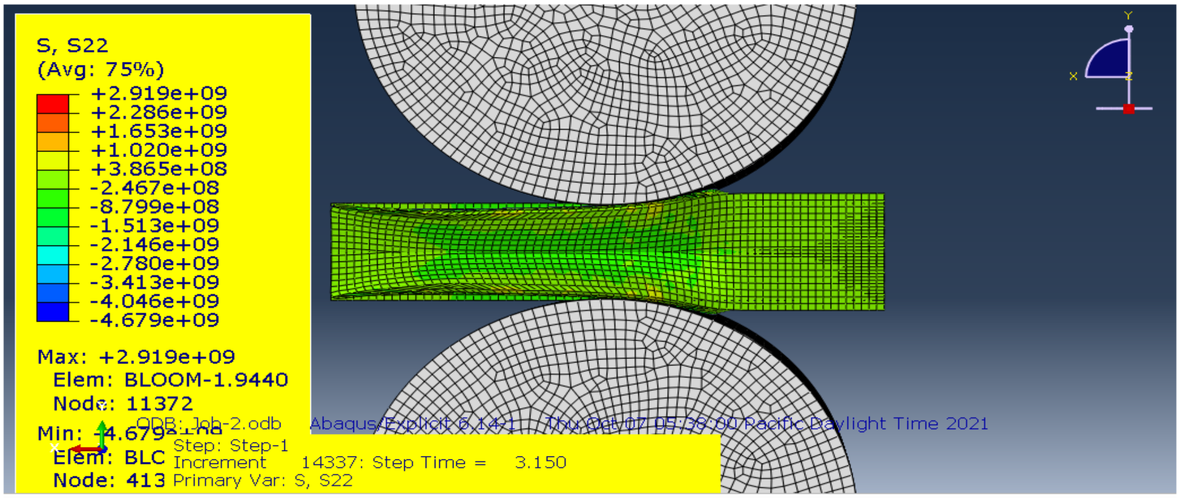


Figure5. 13 : Plastic strain in y- direction, with the maximum and minimum value of node number and max and min strain value.

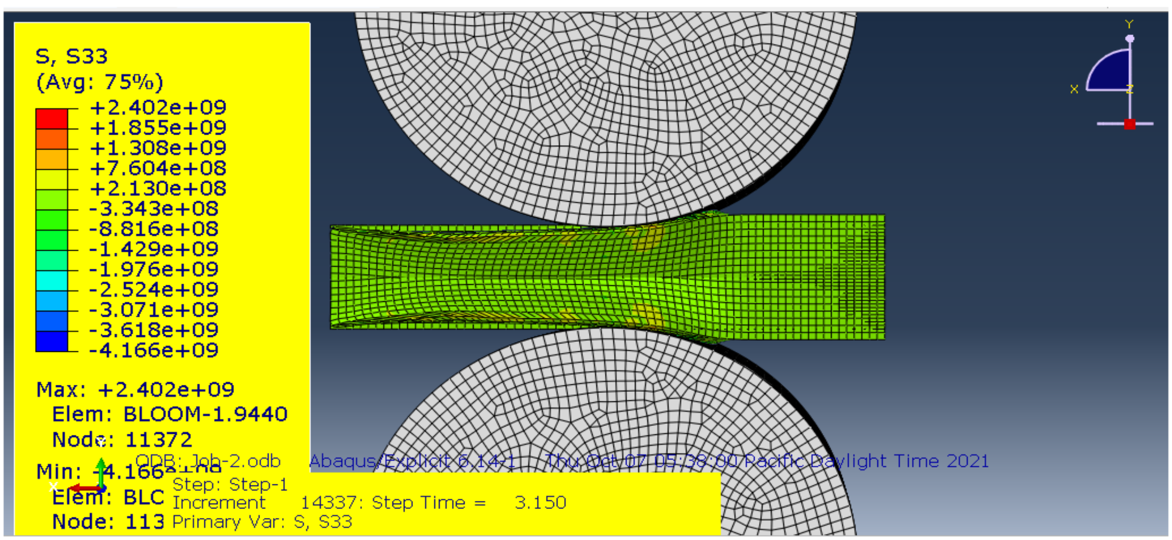


Figure5. 14 :Plastic strain in z- direction with the maximum and minimum value of node number and max and min strain value.

The material is constrained in the z-direction, i.e. the material is not extended in the width direction as in the length. Thematerial gets longer and not wider more. Plastic strain distribution in specific direction and strain distribution was recorded and investigated. The maximum plastic strain occurred at top and bottom areas and a minimum occur along the center horizontal axis. Specific strain components of the strain tensor can be displayed for the three normal strains. In the x-direction (Figure5.12), the maximum compressive plastic strain was at the bloom center, while smallest plastic strain happened on the bloom sides, which were not contacted with the mills. Plastic strain in the y-direction (Figure5.13) was a mixture of tension at the bar center and compression on the surfaces. During this rolling process, material at the central portion of the bar moved towards the surface, while surface friction at the roll caused internal tension and compression at the surface in y-direction. In the z-direction (Figure5.14), the steel bloom was elongated parallel to the rolling direction, and plastic strain in z-direction varied in a small range (2.402e8–(-4.166e9)).At the place where the bloom and roller contact each other the maximum value of node constant 11372 and minimum value of node constant vary between 113-413.

The relationship between stress and strain of plastic process, and the relationship between their increments were expressed by the constitutive equations based on incremental or known as flow. It is evident that the deformation in the roll bite is inhomogeneous. The effective strain increases from the entry to the roll bite at the exit.

Elastic deformation occurs in the initial portion of a stress-strain curve, where the stress-strain relationship is initially linear. In this region, the stress is proportional to strain. Mechanical behavior in this region stress-strain curve is defined by a basic physical property called the modulus of elasticity (abbreviated as E). The modulus of elasticity is the slope of the stress-strain line in this linear region, and it is a basic physical property of all materials. It essentially represents the spring constant of a material. The modulus of elasticity is also called Hooke's modulus or Young's modulus. Region where indicate that the linear relationship between stress and strain begins to break down the proportional limit which is a transitional point to the plastic deformation to happen or the stress-strain curve, linearity ceases, and small increase in stress causes a proportionally larger increase in strain. If the force is reapplied, the trace of the stress and strain points increases along the original line. However, if the deformation the work piece has been stressed above the elastic limit (EL), plastic deformation will have occurred, and there will be a permanent change in the stress-strain behavior of the deformed piece in subsequent compressive load applied by roller. Then the curve reaches the proportional limit and later the elastic limit. Plastic strain increment (flow) in any small time increment is proportional to the instantaneous Stress.

Roller is considered to be rigid with no friction and work piece material is assumed to be plastic, meshed with quadrilateral plane strain elements**.** Finite element simulation was also performed to indicate that full recrystallization and no accumulation of residual stress and strain. The plastic strain distribution is the results from the accumulated strain simulation. The plastic strain is larger at the bloom surface than at the bloom mid-thickness. For the no strain accumulation condition, the plastic strain differences between the bloom surface and bloom mid-thickness for each successive roll pass are comparable. The maximum plastic strains determined for pass indicates that have a largest deformation and the plastic strain is almost doubled compared to the other rolling passes. During the simulation of the hot rolling process, which involves large deformation, some elements soon become much distorted and are not appropriate for further computation. It is very often necessary to regenerate the mesh several times in order to complete the simulation. For very complicated industrial parts, tetrahedral elements seem more convenient for automatic meshing and remeshing. Flow stress functions may be divided into a number of groups differing type and taking into account the parameters describing initial conditions and the development of the material from the initial state. The displacements, strains and stresses in a deformable body are interlinked.

5.7 Effects of Speed

Rolling speed is an important parameter for hot rolling, since this factor directly controls the strain rate, flow stress, heat of deformation and heat transfer coefficient. Depending upon the speed of the roller the strain of the rolled materials will be modifying. Here in result, the flow stress of bloom with respect to high rolling speed. Rolling speed is an easily variable parameter it has great effect on heat transfer, flow stress, roll force, meshing etc. Because of less contact time and high heat developed by the higher relative velocity. The speed increases, temperature of the mild steel bloom also increases. The temperature increases after the work piece moved between rollers at various speed. Rolling speed directly controls the parameters such as the Strain rate, flow stress, heat of deformation and interface heat transfer. Hence the rolling speed is one of the most important parameter that influencing the hot rolling. Increasing the rolling speed, the work piece roller contact time is shortened, yielding to a decreased amount of heat flux transferred to the roller surface; the occurrence of which results in a higher surface temperature. An increase in the value of rolling speed parameter leads to an increase in the bloom temperature and consequently decreasing the flow stress of the material which is resulted that the material becomes, the lower rolling load and lower power are required. Increasing the roller angular velocity has reduced the required load for rolling of the steel bloom to a similar reduction during the hot rolling because lower power required. Decreasing the rolling speed, the work piece-to-roller contact time increases, and as a result, the heat flux transferred to the roller material is increased, causing the surface temperature of rolled materials under lower rolling speeds to become lower. By increased speed the temperature of the rolling increase, affects the flow stress which resulted by decreased the effective strain.

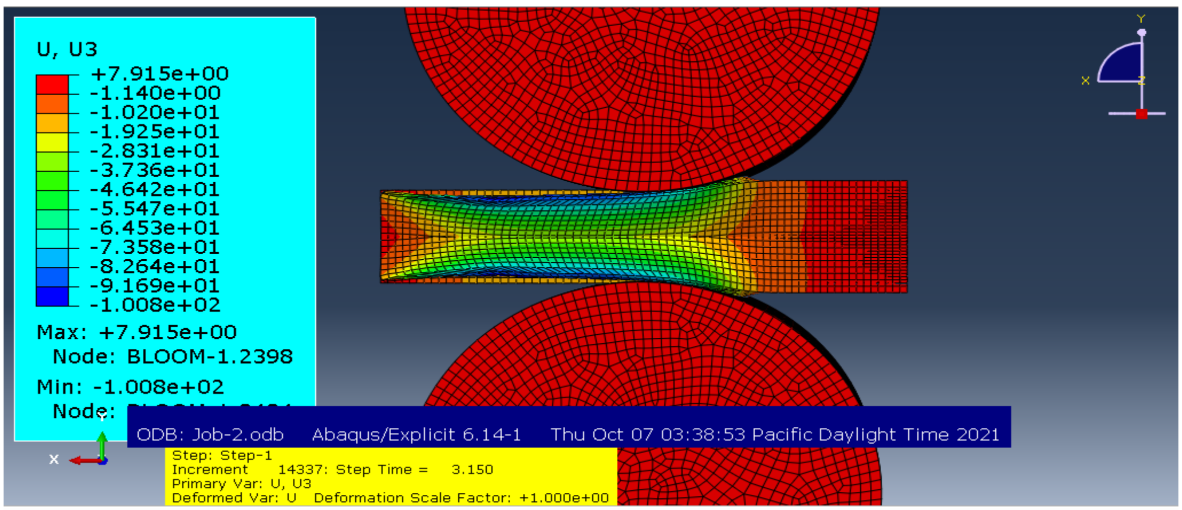


Figure5. 15 :The velocity of the rolls equals the velocity of the work piece (definition of neutral plane).

Figure 5.15 clearly shows how the plane in which the velocity of the rolls equals the velocity of the work piece (definition of neutral plane) actually has a shape against the belief in the classical rolling theory that plane sections remained plane. The numerical results for the interest, namely, equivalent Mises stress, maximum strain rate, temperature increase, bloom length increase, bloom width increase (spread), % reduction achieved after rolling, and bloom velocity increase, and the main conclusions obtained from the above figures 43 corresponding to the 3D hot rolling. Figure 43 shows that increasing the rolling speed cause the point having the maximum stress to get closer to the maximum strain rate point. Increasing the rolling speed causes the bloom and the roller to be in contact for less time. As a result, it decreases the heat flow from the bloom to the roller. In addition, if the rolling speed increases, the strain rate will increase as well. Because of increase in the strain rate, the internal heat generation rate enhances. By paying attention to Figure 5.15 and the preceding remarks, it can be concluded that the effect of the strain rate is predominant in this case.

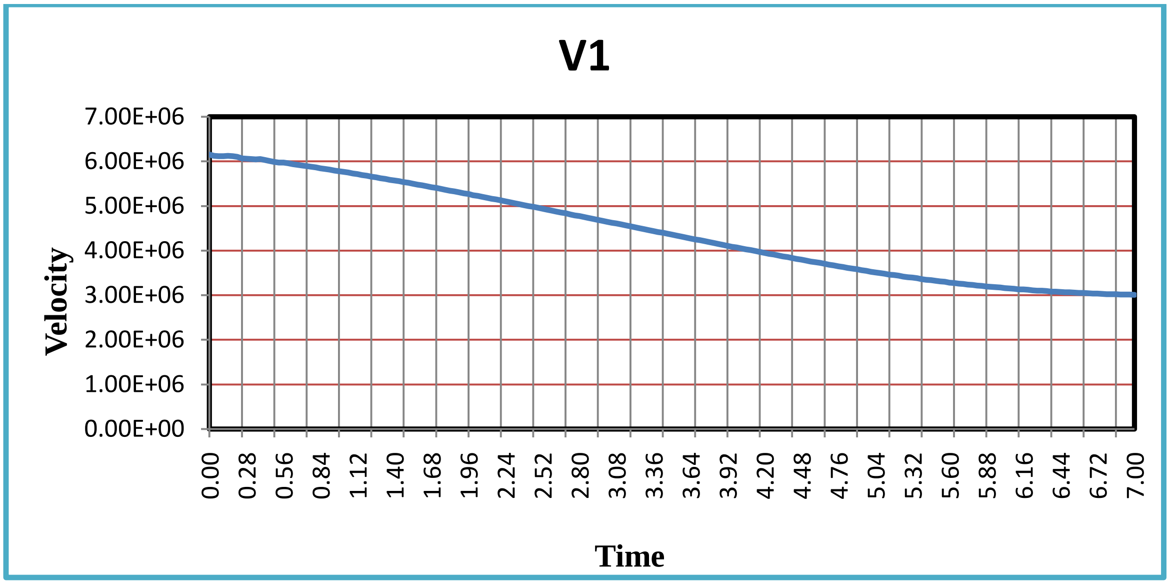


Figure5. 16 : Rolling speed of bloom can have in the x- direction of plane axis (x=V1).

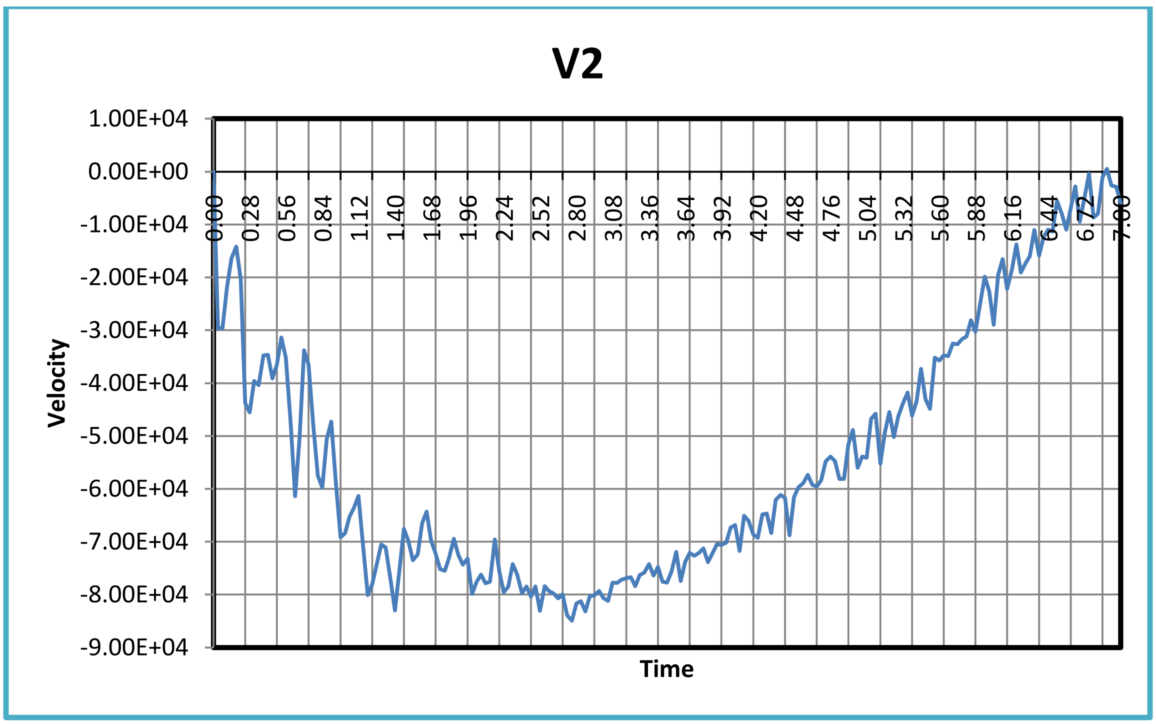


Figure5. 17 :Rolling speed of bloom can have in the y- direction of plane axis (y=V2).

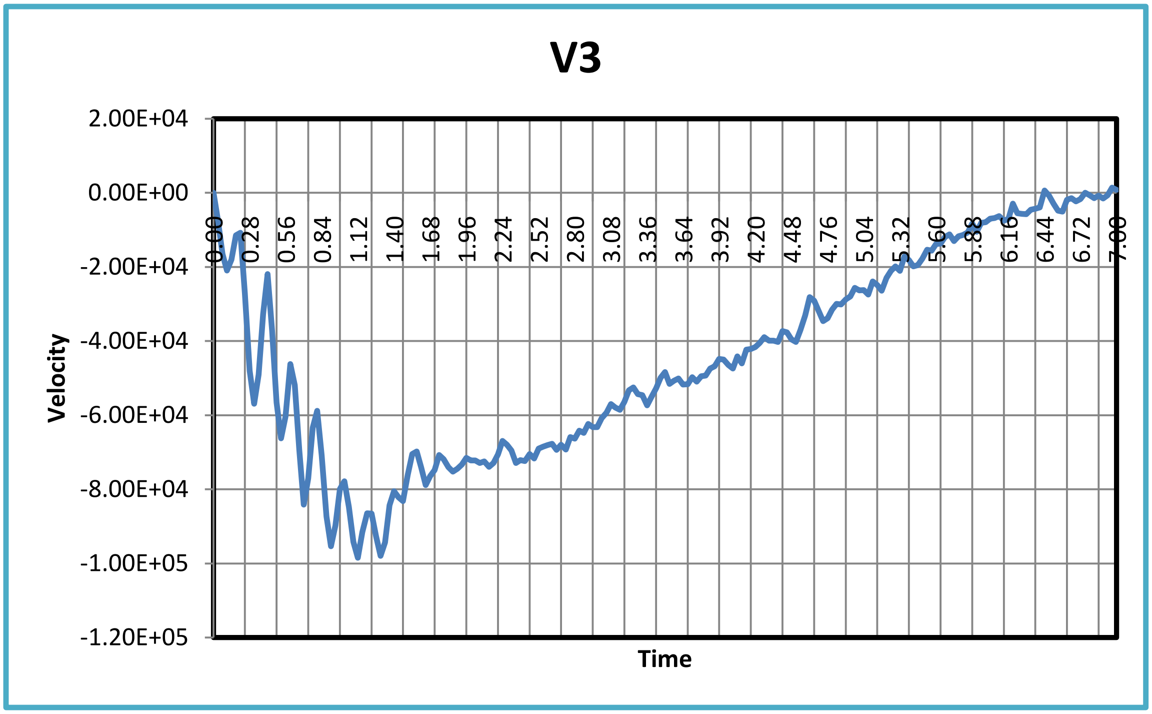


Figure5. 18 : Rolling speed of bloom can have in the z- direction of plane axis (z=V3).

The exit speed of stock is greater than the peripheral speed of rolls. Since on the entry side the stock passes through with a speed less than the horizontal component of the peripheral speed of rolls, there must be a place in the roll gap at which this horizontal component of peripheral speed is equal to the speed of rolled stock and This place is called the neutral line or plane, δ denotes the neutral angle, i.e. the angle determining the position of the neutral line relative to roll axis. Results from rolling speed simulations in ABAQUS indicate rolling speed causes few changes in the response. As rolling speed is increased the stress distribution remains the same. These simulations using ABAQUS show the aforementioned parameters have different effects on rolling processes. In general, the steel bloom has higher stress and mild steel is suitable for rolling because it elongates significantly and the equivalent plastic strain has inverse relation with roller speed, whereas roller speed increases the equivalent plastic strain decreases.

CHAPTER 6

Conclusion and Recommendations

6.1. Conclusions

The main goal of this work is the need the mechanisms that govern the hot rolling process which are not properly understood still, and there exists a need to provide comprehensive way that allow them to predict the influence of different parameters that applied or involved in the rolling process and reducing the number of trials in the rolling, and increasing the confidence in the manufacturing process and the quality of the final product. This models developed by concerned all of the non-linearities present in the rolling problem: material, geometric, boundary, and heat transfer, and used a coupled thermal-mechanical analysis method to take into account the coupling between the mechanical and thermal phenomena resulting from the pressure-dependent thermal contact resistance between the work piece and the work- rolls. The goal of this work was to develop finite element model of the hot flat rolling processes that can be used to analyze the rolling process under a series of changing parameters. Through our analysis, we were able to demonstrate the goals of this thesis: That the steel in hot rolling can be modeled using the rigid-plastic material model with the flow stress as a function of the strain, stress, temperature, using also the von Mises yield surface and as well as other parameters of interest, on the work piece can be predicted, as we measured them through the simulations. The heat transfer from the work piece to the rolls can be analysis by incorporating all the thermal boundary condition properties of the rolls and the bloom into finite element model to take into account conduction, convection, radiation, and plastic work heat generation. The finite element method can be used to predict material flow, plastic material model to simulate the flow stress of steel at rolling temperatures. The finite element approach to solving the problem, which was done by translating the engineering science and mechanics issues of the problem into two initial boundary value problems (mechanical and thermal) which were solved using a variational approach that led to the finite element discretization equations that were implemented into the finite element formulation. The final solution will be determined by the simultaneous solutions of two initial boundary value problem of mechanical and the thermal problems due to the strong coupling between them. In order to do this, we took advantage of the solid & flow formulations for the mechanical problem, and also from the FEM formulations for the heat transfer and the coupling and formulations were used to calculate the temperature distribution as well as the velocity, strain and stress fields in the deformation zone during the rolling and the models have been showing that computed distributions of the equivalent stress, strain, etc, are accurate valid. Consequently, the finite element models developed have allowed us to obtain a greater understanding all the issues involved with non linear finite element modeling applied to rolling, namely, the modeling of the material, the types of plastic models used, yield surfaces, the types of finite element method elements needed to model the problem in, the setup of the contact parameters within the software in order to achieve convergence. As it is observed there is a complex interconnection between stress- strain that predicted easily in the rolling of bloom mild steel and the models have been developed which are able to solve, non linear, dynamic, steady state, transient, isothermal as well as non isothermal problems to analysis the simulation (the description and reproduction of physical and technical processes by use of mathematical and physical models) that carried out by a coupled thermo-mechanical FE method using commercial FE software package ABAQUS. The capability of obtaining detailed solutions of the mechanics of plastic deformation of a metal, namely, to determine strains-stresses relationship, temperatures, velocities, by using FE method. In general the present the major innovation of this work is modeling horizontal hot rolling by utilizing a coupled thermo-mechanical 3D FEM and FEA of the rolling process and determine strains-stresses relationship, temperatures, and velocities as a whole, i.e. from the entry to the exit of the horizontal rolling single pair roller stands. In this work the model of the bloom and roller using FE approach for the coupling of thermal & mechanical behavior of the bloom in the rolling was developed. The study was performed on the effect of different rolling parameters on the deformation behavior of bloom with emphasis on the thermo-mechanical stresses developed within the work piece during the operation. Simplified governing equations for bloom rolling analysis are derived from the hot flat rolling process description, and then a simulation study of the rolling process is presented. A flat hot rolling analysis was completed, then plane-strain rolling of bloom structures. The plane strain study of flat rolling provides a clear understanding how the selected parameters affect each other and the deformation process. The significance of this work can be stated that both mechanical and thermal loadings during the hot rolling operations, both are remarkable phenomena influencing the deformation behavior of the rolling process especially in metal forming process. The rolling speed acts as a more influential parameter on the thermo-mechanical behavior of the rolling means that by increasing the value of rolling speed for a constant initial temperature, the developed thermal stress within the bloom increases, while mechanical stresses are reduced. In this study the detail examination on the values of coupled thermo-mechanical stresses developed within the work piece revealed that the effect of both mechanical and thermal loads should be taken into consideration, in case a more accurate prediction of the effect of different parameters that applied during the rolling operation and roll material selection are to be conducted in the rolling operations. The thermo-mechanical part of the modeling is based on a coupled FEM solution of the rigid-plastic-flow formulation and general heat-transfer equation describing the temperature field in the deformation zone. The ASTM A36 mild steel (bloom) behavior is modeled using a rigid-plastic flow formulation based on the von Mises model to be rigid, and thermo-mechanical boundary conditions are implemented in the model. The followings are concluded from the thermo-mechanical coupled process and finite element analyses of hot rolling by using FE models which provide variable and parameters effect values depending on the above analysis can be summarized as follows:-

The significance of the present work can be stated to be the investigation of both mechanical and thermal loadings during the hot rolling operations, as these both are remarkable phenomena influencing the deformation behavior of the rolling mills in this particular metal forming process. The desired final mechanical and geometrical properties of the rolled stock rolling schedule dependent on the amount of reduction, the rolling velocity, the temperature and the quality of final product is highly dependent on the thermo-mechanical deformation and flow stress behavior during hot rolling. The rolling process is simulated by using the finite element method with relatively short computing time, simulation conducted by the complete 3D finite element method.

- Model of the bloom and roller using finite element approach for the contacting leads realized that the combination of thermal & mechanical behavior of the roll and bloom in the hot rolling.
- Simulation of metal forming processes involves deformation analysis and FEM for a consistent analysis of thermo- mechanical deformation model has been used to

represent the flow type behavior of metals at elevated temperatures and integration of the rate constitutive equations is carried or involved.

- Analysis the bloom mild steel using finite element method has been conducted using ABAQUS and the results has been obtained that from the stress-strain graph it is understood that the bloom mild steel follows the Hooke's Law i.e., stress is directly proportional to strain.
- The use of FEM software to simulate a hot rolling allowed determining the distribution of effective stress, effective plastic strain, and rolling cross-section area of the bloom at roll pass.
- The use of FEM software to simulate hot rolling allowed determining the distribution of stress, effective plastic strain, of the bloom during rolling pass.
- The FEA model the values compared with the experimental result found to be good agreement with experimental value and the stress contour in the compressive direction of horizontal rolling process, which shows that the highest stress is located in the contact area of bloom and roller during rolling.
- Finite Element Method simulations are increasingly adopted to make this process more efficient and to test potential rolling sequences, achieving good accuracy during simulation times, limiting the practical use of the approach.
- In this work we supervised learning approach to predict the deformation of a given work piece by a set of rolls with a given geometry; the model is trained on a large dataset of procedurally-generated FEM simulations.
- When the rollers are rotating at a constant angular velocity, the bloom is moved between the roller and it is subjected to high compressive stress as a result of deformation. It was shown that the rolling speed and temperature acts as a more influential parameter on the thermo-mechanical behavior of the hot rolling. The results indicated that by increasing the value of this parameter the developed thermal stress within the roll material increases, while mechanical stresses are reduced.

6.2. Suggestions for Further Study

Even though the hot rolling is applied more for large deformation thickness reduction, but still number of variations are possible that are needed to be corrected. A coupled thermo-mechanical could be used by other forms of complex manufacturing, by utilizing a systematic method by which work pieces can be manufactured economically and competitively from raw material (initial stages), through to the desired shape or finishing stages. The direction of future trends has been indicated in this thesis (work). The need for further effort in research and development of coupled thermo-mechanical process hot roll is obvious. The following can be done to further improve coupled thermo-mechanical process. Only the basic principles of the coupled thermo-mechanical process approach have been discussed at this stage. Full hot rolling includes thermal-mechanical elements and so on. So, more sections need to be added to the matrix to encompass these aspects. This should be addressed in further research. Training is a prominent concern linked with successful coupled thermo-mechanical process hot rolling. Improvements can be made by standardizing the databases used, facilitating more effective communication. In addition the approach should be more users friendly. TMP is the sophisticated combination of well defined deformation operations and well defined heat treatment in a single production stage requires the integration of coupled TMP skills as well as the integration of computer skills and related technology. In the long run, effective use of ABAQUS software will allow coupled thermo-mechanical hot rolling process to be both more marketable and attractive visually. A full thermo-mechanical analysis is necessary to model the material flow, stress and temperature correctly throughout the whole process that resulting finite element models take into account the flow stress of the rolling bloom at the initial rolling temperature of operation. Since under metal-forming operation especially during the hot rolling process, a large amount of the mechanical work is converted into heat through large plastic deformations and through friction forces between the interface area work piece and roller because heat generated needs significant consideration due to heat transfer takes place from the work piece to surroundings or to the roller in hot rolling and the distribution of temperature in the material is changed due to generation of heat that arises from plastic deformation, because most materials have flow stresses that are temperature ,strain and strain rate dependence to solve the problem combined the deformation model of thermo-mechanical analysis (deformation and heat analysis) iteratively until both solutions converge to obtain a more realistic simulation of the metal-forming process. Another extension of the study can be about the material of the bloom. The deformation features of the bloom can be analyzed with different materials having different yield stresses. By this way, effect of yield stress on the plastic deformation of the bloom can be examined. In the metal industry, the hot rolling operation is often carried out in different high stand passes. The simulation of multi-pass bloom rolling would yield more realistic results. This could be done by two methods. One method would be to a setup, in which the bloom would pass through two high stand rollers. A second method would be setting the initial conditions of the work piece equal to that in the final rolling work piece in the first operation. In ABAQUS, the process would require adding another roller to the setup. The initial condition parameter could be used to input a state of residual stresses into the bloom. The thermo-mechanical FE code is applied for the hot rolling process and simulation process starting with an analysis of rolling of the result. If the rolling proceeds too fast, the temperature and strain rate can locally reach the limit where the load-carrying capacity of the work piece is exceeded.

REFERENCE

[1] Y. F. Aoda and L. S. Jabur, "Effect of the Rolling Direction and Draft on Some of the Mechanical Properties for the Medium Carbon Steel," vol. 3, no. 12, pp. 2425–2431, 2014.

[2] R. A. H. M.Met., "TEMPERATURE AND STRUCTURAL CHANGES DURING HOT ROLLING," no. November, 1976.

[3] F. Micari, "Three-dimensional coupled thermo-mechanical analysis of hot rolling processes," vol. 34, pp. 303–310, 1992.

[4] A. R. Shahani, S. A. Nodamaie, and I. Salehinia, "Parametric Study of Hot Rolling Process by the Finite Element Method," vol. 16, no. 2, pp. 130–139, 2009.

[5] A. Mechanics and A. Arbor, "FINITE ELEMENT FORMULATION FOR THE SIMULATION OF HOT SHEET METAL FORMING PROCESSESj-," vol. 26, no. 2, pp. 143–161, 1988.

[6] M. Engineering and T. Rourkela, "Numerical Analysis of Work Roll Cooling in Hot Rolling Process Numerical Analysis of Work Roll Cooling in Hot Rolling Process," no. June, 2012.

[7] S. Kumar, "A Study on Thermo-Mechanical Analysis of Hot Rolling & Estimation of Residual Stresses by using FEM," vol. 9, no. 3, pp. 26–34, 2013.

[8] Y. Licheng, J. I. Jinchen, and H. U. Jinxiang, "Formation Mechanism in Alloy Steel Rolling Process Using Thermo-mechanical Coupling Method 2 Finite element method of," vol. 27, no. 3, pp. 422–423, 2007,

[9] N. K. and K. M. Jian-guo CAO, Jie ZHANG, "Finite element analysis of strip and rolling mills."

[10] M. Rout, S. K. Pal, and S. B. Singh, "Cross Rolling : A Metal Forming Process,"

[11] T. Li, H. Li, R. Li, Z. Wang, and G. Wang, "Work Roll Surface Profile Design and Optimization for Hot-core Heavy Reduction Rolling Process," vol. 59, no. 7, pp. 1314–1322, 2019.

[12] B. Koohbor, “Finite element modeling of thermal and mechanical stresses in work-rolls of warm strip rolling process,” *Proc. Inst. Mech. Eng. Part B J. Eng. Manuf.*, vol. 230, no. 6, pp. 1076–1086, 2016,

[13] A. K. Kumar, “STRUCTURAL SHAPE ROLLING ISSN No : 2348-4845,” vol. 3, no. February, pp. 111–117, 2016.

[14] “Modelling Plastic Deformation of A36 Mild Steel Under Extrusion Process,” no. February, 2016,

[15] R. Kuziak, Y.-W. Cheng, M. Glowacki, and M. Pietrzyk, “Modeling of the microstructure and mechanical properties of steels during thermomechanical processing,” *NIST Tech. Note(USA)*, no. 1393, p. 80, 1997, [Online].

[16] S. Riljak, “Numerical Simulation of Shape Rolling.”

[17] A. A. Permanasari, P. Puspitasari, and M. A. Choiron, “The modeling and optimization of hot rolling process of A36 structural steel by using response surface methodology,” vol. 07018, 2018.

[18] F. Sandberg, “Thesis Master ’ s degree in material engineering Finite element analysis of hot rolling in the blooming mill,” 2016.

[19] A. R. Muñiz, “NON-LINEAR FINITE ELEMENT METHOD SIMULATION AND MODELING OF THE COLD,” 2007.

[20] L. Wang, X. Zhu, D. Zhao, and D. Zhang, “An analytical model of plate rolling force with a simple available velocity field and equal perimeter yield criterion,” vol. 9, no. 9, pp. 1–8, 2017,

[21] L. C. J.G Lenard, M.Pietrzyk, “Mathematical and Physical Simulation of the Properties of Hot Rolled Products.”

[22] R. Leardi, L. Diviani, and F. Berto, “Design of Experiment as a powerful tool when applying Finite Element Method: a case study on prediction of hot rolling process parameters,” vol. 44, pp. 1–15, 2018.

[23] K. Komori, “SIMULATION OF DEFORMATION AND TEMPERATURE,” no.

September, pp. 11–14, 2000.

[24] X. Wang, K. Chandrashekhara, S. A. Rummel, S. Lekakh, D. C. Van Aken, and R. J. O. Malley, "Modeling of mass flow behavior of hot rolled low alloy steel based on combined Johnson-Cook and Zerilli- Armstrong model," *J. Mater. Sci.*, vol. 52, no. 5, pp. 2800–2815, 2017.

[25] D. Demin, I. Zakhariev, T. Labutina, and A. Levikina, "NUMERICAL SIMULATION LABORATORY HOT ROLLING PROCESS OF A ROUND BARS IN FLAT ROLLS," pp. 380–385, 2018.

[26] A. R. Licheng Yang*, Jinchen Ji**, Jingxiang Hu***, "Effect of process parameters on mechanical behavior in hot-slab rolling," vol. 17, no. 5, pp. 474–479, 2011.

[27] R. Kuziak, Y.-W. Cheng, M. Glowacki, and M. Pietrzyk, "Modeling of the microstructure and mechanical properties of steels during thermomechanical processing," no. 1393.

[28] D. E-theses, "Rolling mill roll design," 2001.

[29] V. Skliar, "PHYSICAL AND COMPUTER MODELING OF A NEW SOFT REDUCTION PROCESS OF CONTINUOUSLY CAST BLOOMS," pp. 589–594, 2015.

[30] J. Ren, W. Wang, and R. Liu, "Application of DEFORM-3D Finite Element Analysis in Optimization Design for Steel Rolling Production," vol. 8, no. May, pp. 683–690, 2013,

[31] V. N. Danchenko, "NATIONAL METALLURGY ACADEMY of UKRAINE," 2007.

[32] R. Pernis and J. Kasala, "Deformation distribution in rolling zone," no. December, 2015.

[33] A. K. P. M. Kumar, "STRUCTURAL SHAPE ROLLING ISSN No : 2348-4845," vol. 2, no. October, pp. 32–36, 2015.

[34] U. Nations, E. Programme, G. Environment, and T. Energy, "Energy Efficient Technologies and Best Practices in Steel Rolling Industries (Indonesia)."

[35] R. Kumar, A. Joshi, and U. Gurnani, "Review on cold rolling mill roll deformation," no. 1, pp. 5–12, 2015.

[36] U. S. Dixit, “Challenge in the modeling of metal forming processes,” pp. 1–89.

[37] X. Wang, K. Chandrashekhara, S. A. Rummel, S. Lekakh, D. C. Van Aken, and R. J. O’Malley, “Modeling of mass flow behavior of hot rolled low alloy steel based on combined Johnson-Cook and Zerilli-Armstrong model,” *J. Mater. Sci.*, vol. 52, no. 5, pp. 2800–2815, 2017.

[38] N. Arab, “Simulation of Steel Sheets Cold Rolling in Sticky Friction Conditions to Reduction of Scrap and Tools Wear,” vol. 4, no. 2, pp. 39–45, 2020.

[39] S. Dwivedi and G. Agnihotri, “Parametric Study of the Hot Rolling Process Using FEM,” *Int. J. Eng. Res. Appl.*, vol. 2, no. 5, pp. 1517–1522, 2012.

[40] Ö. NECATİCORA, “FRICTION ANALYSIS IN COLD FORGING,” no. December, 2004.

[41] W. T. Wu, J. T. Jinn, C. E. Fischer, S. Forming, and T. Corp, “Modeling Techniques in Forming Processes,” 2003.

[42] X. Ke, “FE Simulation Based Friction Coefficient Factors for Metal Forming,” no. August, 2013.

[43] U. Information, “Volume A : Theory and User Information,” 2013.

[44] M. J. Ltd, “MSC.Marc Volume A: Theory and User Information, Version 2001,” vol. Volume A, 2001.

[45] D. Maciejp. J. G. L. PIETRZYK, *Thermal-Mechanical Modelling of the Flat Rolling Process*. .

[46] J. Minato-ku, Tokyo 107-0052, “MSC.Marc Volume A: Theory and User Information, Version 2001,” 2001.

[47] J. G. L. Maciej Pietrzyk, *Thermal-Mechanical Modelling of the Flat Rolling Process*. .

[48] D. K. H. Schroder, “A BASIC UNDERSTANDING OF THE MECHANICS OF ROLLING MILLS ROLLS.”

[49] Z. Wusatowski and D. Se, “PHENOMEN A OCCURRIN G DURIN G PLASTIC

WORKIN G OF METALS."

[50] H. Melting and T. Alloys, "PART II : TECHNOLOGY."

[51] M. Software, "Marc® 2013 Volume A : Theory and User Information," pp. 82–85, 2013.

[52] Avda, "A STUDY OF FRICTION MODEL PERFORMANCE IN A," vol. 17, pp. 569–582, 2018.

[53] E. Parteder, A. Binder, G. Wollendorfer, T. Antretter, and K. Zeman, "Hot Rolling and Accelerated Cooling Simulations using ABAQUS – a Fertile Basis for Fast Online Algorithms in Heavy Steel Plate Production," pp. 1–14, 2013.

[54] MSC.MARC, "MSC.Marc Volume A: Theory and User Information, Version 2001," 2017.

[55] M. Pietrzyk and J. G. Lenard, *Thermal-Mechanical Modelling of the Flat Rolling Process*. 1991.

[56] T. Kobayashi, S., Oh, S.K. and Altan, *Metal Forming and The Finite-Element Method, Oxford University Press Inc.* 1989.

[57] P. Hartley and I. Pillinger, *Numerical Modelling of Material Deformation Processes*. London Berlin Heidelberg N ew York Paris Tokyo Hong Kong Barcelona Budapest.

[58] L. C. J.G.Lenard, M.Pietrzyk, "Methematical &Physical Simulation of the Properties of Hot Rolling Products," 2554, [Online].

[59] P. Hartley and I. Pillinger, *Numerical Modelling of Material Deformation Processes*. .

[60] M. P. J. G. Lenard, *Thermal-Mechanical Modelling of the Flat Rolling Process Springer-Verlag*. .

[61] G. E. Dieter, D. Bacon, and G. L. Wilkes, *McGraw-HillSeries in MECHA NICALMETALLURGY Materials ScienceandEngineering*. .

[62] J. A. De Castro and L. P. Moreira, "Modelling the hot rolling process using a finite volume approach," vol. 59, pp. 419–428.

[63] J. Fritz and D. H. Russ, "Computer Modeling of the Temperature Profile During the Ring

Rolling Process," 2000.

[64] R. M. M. C. M. Eking and J. R. Rice, "FINITE-ELEMENT FORMULATIONS FOR PROBLEMS OF LARGE ELASTIC-PLASTIC DEFORMATION," vol. 11, no. May, 1974.

[65] I. Y. T. Kim S. Y., "Three-Dimensional Finite Element Analysis of Non-Isothermal shape rolling, Journal of Materials Processing Technology 127, 2002," 2003.

[66] A. saboonch. & A.H.Meghdadi, "Significance of Hot Conduction Parameter along the Rolling Direction in the Thermal Modeling of the Hot Rolling Process," vol. Volume 4, p. pp.1-7, 2007.

[67] C. V. N. · W. Z. · L. M. Alves and N. B. · P. A. F. Martins, *Modeling of Thermo-Electro-Mechanical Manufacturing Processes*. .

[68] M. K. Majumder, P. R. More, S. Chatterjee, P. S. Mandley, and S. K. Pal, "Roll separating force in hot rolling under grooved rolls -A finite element analysis and experimental validation," vol. 23, no. August, pp. 267–273, 2016.

[69] Y. W. Cheng, R. L. Tobler, B. J. Filla, and K. J. Coakley, "Constitutive Behavior Modeling of Steels Under Hot-Rolling Conditions."

[70] S. Biswas and T. Committee, "Simulation of Thermo-mechanical Deformation in High Speed Rolling of Long Steel Products," 2003.

[71] L. Yang, J. Ji, J. Hu, and A. Romagos, "Effect of process parameters on mechanical behavior in hot-slab rolling," vol. 17, no. 5, pp. 474–479, 2011.

[72] M. Bagheripoor and H. Bisadi, "An investigation on the roll force and torque fluctuations during hot strip rolling process," *Prod. Manuf. Res.*, vol. 2, no. 1, pp. 128–141, 2014., [73] M. Bagheripoor and H. Bisadi,

"An investigation on the roll force and torque fluctuations during hot strip rolling process," *Prod. Manuf. Res.*, vol. 2, no. 1, pp. 128–141, 2014.

[74] O. C. Zienkiewicz and F. Emeritus, "The Finite Element Method Fifth edition Volume 2 : Solid Mechanics," vol. 2.

[75] L. Jing, "Jing, Limei (2001) Rolling mill roll design, Durham theses, Durham University," *E-Theses Online*, pp. 1–130, 2001.

[76] N. Padhye, D. M. Parks, A. H. Slocum, and B. L. Trout, "On Cold-Rolling (Bonding) of Polymeric Films : Numerical Simulations and Experimental Results," pp. 1–80.

[77] X. Duan, "Some Problems In Hot Rolling Of Al-Alloys The Finite Element Method Solved By A thesis submitted in partial fulfilment of the requirements of Bournemouth University for the degree of Doctor of Philosophy," no. November, 2001.

[78] J. Rasty, "Experimental and Finite Element Study of Residual Stresses in Zircaloy-4 (r) and OFHC Copper," vol. 4, 1987.

[79] M. Marc, "Volume A: Theory and user information," *Msc. Software, Palo Alto, USA*, 2001, [Online]. Available:

[80] P. V. R. R. Reddy, G. C. M. Reddy, and P. R. Prasad, "A Review on Finite Element Simulations in Metal Forming," vol. 2, no. 4, pp. 2326–2330, 2012.

[81] J. and M. S. R. J.E. Jackson, *The Rigid-Plastic Finite-Element Method for Simulation of Deformation Processing*. .

[82] O. C. Z. L. T. D. J.Z.Zhu, *The Finite Element Method: Its Basis and Fundamentals Seventh Edition*, Seventh Ed. .

[83] O.C.ZIENKIEWICZ & R.L. TAYLOR, Ed., "The FINITE ELEMENT METHOT," vol. VOLUME 2.

[84] Pdf, "METAL FORMING et al , 1982).," 1982.

[85] "Metal forming and the finite-element method."

[86] I. G. L. and M. Pietrzyk, *Numerical Modelling of Material Deformation Processes*. 2018.

[87] M. Rout, S. K. Pal, and S. B. Singh, "Finite Element Analysis of Cross Rolling on AISI 304Stainless Steel : Prediction of Stress and Strain Fields," no. Aimtdr, pp. 1–6, 2014.

[88] S. Toledo, *Handbook of Nonlinear Analysis (Solutions 106 and 129)* . .

[89] J. J. Park and S. I. Oh, "Application of Three Dimensional Finite Element Analysis to

Shape Rolling Processes," no. FEBRUARY 1990, 2019.

[90] B. Koohbor and S. Serajzadeh, "Thermomechanical behaviours of strip and work-rolls in cold rolling process," *J. Strain Anal. Eng. Des.*, vol. 46, no. 8, pp. 794–804, 2011.

[91] JAN EGBERT DEJONG, "Numerical analysis of metalforming processes : applications and experimental verification," no. 1983, 2020.,

[92] M. A. Guerrero, J. Belzunce, M. C. Betegón, J. Jorge, and F. J. Vigil, "Hot rolling process simulation . Application to UIC-60 rail rolling," pp. 213–218.

[93] N.-M. W. and B. Budiansky, "'Analysis of sheet metal stamping by finite element method', J. Appl. Mech. Trans. ASME, 45, p73 (1978)," no. September, pp. 11–14, 2000.

[94] C. V. Nielsen et al, *Modeling of Thermo-Electro-Mechanical Manufacturing*. 2554.

[95] R. S. Nalawade, V. R. Marje, G. Balachandran, and V. Balasubramanian, "Effect of pass schedule and groove design on the metal deformation of 38MnVS6 in the initial passes of hot rolling," vol. 41, no. 1, pp. 111–124, 2016.

[96] T. Wang, Z. Ren, and D. He, "STRIP-ROLLING PROCESS OF A CONTINUOUS VARIABLE CROWN MILL USING THE COUPLED RIGID-PLASTIC FINITE ELEMENT METHOD," vol. 27, no. 2, pp. 123–132, 2019.

[97] O. C. Z. L. Taylor, *The Finite Element Method for Solid and Structural Mechanics Sixth edition*, Sixth edit. .

[98] C. V. N. · W. Z. · L. M. Alves and N. B. · P. A. F. Martins, *Modeling of Manufacturing Processes*. Lisbon Portugal.

[99] U. S. Dixit, "Uday Shanker Dixit Department of mechanical Engineering Indian Institute of Technology Guwahati 1."

[100] Y. Ozcelik and S. Cakil, "MODELLING OF COLD ROLL PROCESS USING," vol. 3, no. 1, pp. 52–63, 2017.

Appendix A: Important Aspects of the Finite Element Model and the table below provides some details regarding the finite elements models used in this work.

Mesh Domain	Two types of solution techniques are used in solving this problem. The first kind of formulation involves traditional pure Lagrangian formulation where the mesh is constrained to the material. The second kind of formulation combines features of both pure Eulerian formulation (in which the mesh is fixed spatially and the material flows through the mesh) and pure Lagrangian formulation. In this case Adaptive meshing is used and is referred to as the Arbitrary Lagrangian-Eulerian (ALE) formulation. This approach often eliminates excessive mesh distortions that are associated with a Lagrangian analysis involving large deformation. Using this approach, the inlet of the stock was defined with Eulerian constraints in order to permit material flow; the mesh on this face was spatially constrained in all directions. The material on the radial surface of the stock was constrained to the mesh in the direction normal to the free surface but was permitted to flow relative to the mesh in the tangential direction.
Time Dependence	In this work the problem is considered as transient.
Time Integration	Explicit, Dynamics, Adiabatic method is used in this work. In this method a large number of time steps is used with very small increments. This method is suitable for high-speed dynamic events like our case where stress wave propagation requires the increment to of very small size to capture wave propagation. Implicit methods can be very costly in this type of problems especially in the case of three-dimensional formulation.
Dimensionality	A full three-dimensional finite element model is considered in this work.

Mass Scaling	Mass scaling is often used to increase the stable time increment of an non-linear analysis by reducing the effects of mass matrix in the solution but it also contributes to the inaccuracies in the solution especially in the parameters that depends on inertia. The author has carried out a study on the effect of mass scaling on the finite element solution and found the result to be unsatisfactory. In this work we do not use mass scaling.
Adaptive Meshing	Adaptive meshing is often used to control excessive mesh distortion, which often occurs in non-linear problems. In adaptive mass scaling after a certain number of time steps the entire geometry of the body is remeshed. We this method for the ALE formulation only.
Hourglass	One disadvantage of using reduced integration procedure is that it can admit deformation modes, which cause no straining at the integration points. These zero energy modes make the element rank deficient and cause a phenomenon called hour glassing where, the zero energy modes starts propagating through the mesh leading to inaccurate solutions. This problem is particularly severe in hexahedral elements. To counter this small artificial stiffness is attached with the zero energy and is associated with the zero energy deformation modes. This procedure is called hourglass control. In this work, we select the hourglass control as "Stiffness" was used.
Element Type	Three-dimensional, Deformable, Reduced Integration, Linear Hexahedral (Brick) element (C3D8R) is used in this work. There are two advantages of using Reduced integration elements. First, stresses and strains are calculated in the so-called Barlow Points providing optimal accuracy. Second, the computational time is less due to reduced number of integration points.
Material	Stock material is assumed as homogeneous and isotropic material with no porosities.
Rate Dependence	The stock material is assumed to be strain rate dependent.
Plasticity Law	Three main plasticity laws are used in this work. They are Shida [E.2], Modified Shida [E.3] and Lee [E.4].

Hardening Rate	Isotropic
%Plastic Deformation Energy Converted to Heat	In an adiabatic analysis a portion of the energy of plastic deformation converts into heat. In this work we consider this ratio to be 0.90.
Initial Conditions	Two initial conditions are mainly used in this work. They are 1) Initial velocity of the stock i.e. the velocity of the stock when it enters the first stand and 2) Initial temperature of the stock i.e. the temperature of the stock when it enters the first stand.
Material	ASTM A36/Mild steel
Finite Element Characterization	The rolls are considered as analytic rigid surface in this work
Boundary Conditions	Angular velocity of rolls are used as the boundary conditions for this work
Contact Condition	Contact between roll and stock is defined as a contact pair that consists of penalty contact enforcement method, balanced contact surface weighting and finite sliding formulation is used.
Friction Model	Coulomb friction model is used for this work with μ=0.3
Heat Transfer Effects	Heat transfer effects are not considered
Material	Stand is considered as a rigid pin support