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SCHOOL OF MECHANICAL AND INDUSTRIAL ENGINEERING

Roll Pass Design of UIC 60 Rail Using Finite Element Method

By
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Thesis Approval Sheet

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Abstract

In metal forming, a simple geometry, bloom or billet, is plastically deformed between tools to obtain the desired geometry. Hot rolling is one of the main metal forming processes. The rail sections are generally made of carbon steels by hot rolling process. The rolling of rail section is carried out in number of passes. For converting initial steel bloom into final rail section, the bloom is passed between numbers of rollers. Each roller has different grooves on it. The shape of groove decides the rolled section at each pass. So, to get desired section of each pass, I designed the sections which, in turn, reduce its cross-sectional area. The final finishing pass gives the standard UIC 60 rail section used in railways.

The aim of this paper is to present the developed procedure for the simulation of the hot rolling process of UIC 60 rail. The full rolling process of this rail consists of ten shape passes in different grooves, only one pass in each groove (five in roughing stand and five in the finishing stand). The simulation was carried out by using a finite element analysis called DEFORM 3D.

The models developed, take into account all of the non-linearities present in the rolling problem: material, geometric, boundary, and heat transfer. A coupled thermal-mechanical analysis approach is used to account for the coupling between the mechanical and thermal phenomena resulting from the pressure-dependent thermal contact resistance between the steel bloom and the steel rolls.

The model predicts the equivalent stress, equivalent plastic strain, maximum strain rate, equivalent total strain, damage during rolling and bloom temperature increase.

The simulation result were compared with the previous work performed by experiments and other finite element analysis (Ansys). And finally it is found that the DEFORM 3D finite element software is a powerful and reliable software to perform the design of a roll pass for rail. Thus, this procedure is really useful to give assistance in the roll design and to obtain the stock cross-section temperature distribution for the whole rolling process.

Key words: Rail, Rollers, shape rolling, roll pass design, Finite element method (FEM), DEFORM™

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CHAPTER ONE

INTRODUCTION

Rolling is the process of reducing the thickness or changing the cross-section of a long workpiece by compressive forces applied through a set of two rolls that revolve in opposite directions, the space between the rolls being less than the thickness of the entering material. In the rolling process, material passed between rolls is plastically deformed. The rolling process is a widely used industrial process because it makes possible high production and close control of the final product shape and properties. It accounts for about 90 percent of all metals produced by a metal working process. Rolling is one of the oldest processes used in the metal working industry. In view of the tremendous volume and wide variety of rolled products manufactured each year, rolling can be considered to be one of the most important forming processes.

Rolling processes are classified as cold or hot rolling according to whether work hardening occurs. Cold rolling is usually associated with operations performed at room temperature or below the recrystallization temperature at the rolled material. However, hot rolling is usually terminated when the temperature falls to about 50 ° C to 100 ° C above the recrystallization temperature of the material. In this thesis, only hot rolling is considered.

The ultimate goal in hot roll pass design is to manufacture the correct size and shape of a rolled product with a defect free surface and the required mechanical properties. In addition, economic condition must be achieved, for example, maximum output and lowest cost, easy working conditions for the rolling crew and minimum roll wear.

Improvement in the quality and reliability of rolled products can only be achieved through a thorough understanding of the rolling process. This has usually been acquired through practical observations over many years. With the introduction of sophisticated technology, information flows faster than ever. A better understanding of the behavior of the rolled product in the rolling process is considered a key point towards improved quality. This explains why more and more work is being devoted to rolling modelling by both academic and industrial research groups.[19]

This chapter highlights the global and local importance of the metal industry for nations and it also presents the challenges that Ethiopian manufacturing industries are facing. Furthermore, thesis organization, thesis objectives, methodology and the scope and limitation of the thesis work are presented.

1.1. Background and Overview

The annual metal consumption of a nation is an indication of how strong or weak its economy is. Steel industry has played a significant role to the economic growth as a whole through the following primary functions that is as raw materials of processed products for physical infrastructure development such as bridges, highways, seaports as well as airports, railways, electricity's and communications; and as raw materials , or in form of machinery and production utilities, for other industrials needs such as automotive industries, train industries, airplane and ship industries, and other economic sectors for example mining, electricity, gas and clean water supply, construction, and agricultures[1]. The global demand for metals is increasing drastically and the cost of the metal products has also become increasing from time to time in the past few decades and this is one of the challenges which most countries are facing.

The value of production is regarded as one of the important variables for measuring economic activity & development of industrial production. World history proved that industrialization process is mainly driven by steel industries. All countries currently known as industrial countries such as USA, Germany, England, Italy, France, Canada and Australia, as well as those in Asia such as Japan and South Korean are countries with profound steel industries [1]. In our country, manufacturing industries contributes a total value of production amounting to 20.43 billion birr only. Among the industries, the largest share of production value is contributed by manufacturing of food products accompanied by Manufacture of chemicals and chemical products contributing 21.28% and 16.37% respectively. Whereas, manufacture of basic iron and steel contribute only 11.33% of the total value.

In Ethiopia, Manufacturing industries of tanning has earned about 48.7 percent of the total export revenue of the large and medium manufacturing industries. This trend indicates that the export performance of Ethiopian manufacturing industries is still very low and relies on few industries. This situation calls for prompt action concerned bodies and stakeholders to promote and enhance the performance and competence of manufacturing industries both locally and internationally.

Among the total manufacturing establishments included in the survey which is performed by Central Statistical Agency in 2013, 15.2 percent of them were operating below or equal to 25 percent of their capacity, while around 28.3 percent of the establishments have been operating above 75 percent of their full capacity during the survey period. 35.3 percent of the establishments have been utilizing between 51 and 75 percent of their full capacity, whereas

21.2 percent of them were operating between 26 and 50 percent. In general, the survey results indicate Ethiopian manufacturing industries are operating at a low level of capacity. The major reason for low level of capacity utilization in the sector is Lack of demand/market which revealed 35 percent for not operating at their full capacity [2]. One of the reason for lack of demand/market is that most of the manufacturing industries are engaged in producing identical products. Currently there are a lot of long rolled product manufacturing factories in Ethiopia. But they are producing limited and identical product. Due to that they have a lack of market and therefore are operating much below their capacity.

Competitive technology is required to make the products competent enough on the international market. Competitiveness is not determined only by the quality and quantity of a final product but also by how a nation and/or an industry utilizes its human, capital, and natural resources and its productivity. Productivity in turn depends both on the value of products and services as well as the efficiency with which they are produced. The productivity of local industries is of fundamental importance to competitiveness and an effective manufacturing technique and engineering process is vital to the sector.

The value of metals processing as a development tool is based on the principles that they can help a nation achieve enhance its foreign earnings by promoting standard quality product exports, creating jobs and increases income, give opportunity to technology transfer and support other sectors such as the construction industry. Over the years the success of Ethiopian metal industry to achieve these objectives has been limited due to many reasons. However, in the past few years this industry and other engineering sectors have showed a considerable growth in the country following the dramatic development in many sectors and the economic growth of the nation. Regardless of this fact, the demand to supply balance is not yet met in the Ethiopian market and a huge percentage of steel is imported from abroad.

Today most industries around the globe are facing various challenges like design problem. Due to this the products may be limited in variety and low in quality. Therefore it becomes incompatible. i.e.; it does not satisfy the demand at the customers end. Many authors agreed that this design and manufacturing process is becoming increasingly more complex as new knowledge is acquired and new technologies are developed. Those countries which are developed in industrialization will not easily give their design and manufacturing technologies. So our industries should have the access to get design and manufacturing technologies locally.

In the past few years, even though the per capita metal consumption is very low, Ethiopia has engaged itself in an unprecedented infrastructure development. Following this dramatic shift, the construction sector has shown a remarkable boost and the demand for metal, iron and different engineering products has skyrocketed. According to the Ministry of Finance and Economic Development, it has planned to increase the Ethiopian per capita metal consumption from 12kg in 2002 to 34.72kg in 2007 as part of its five years transformation development plans. Metal and engineering industry is the mother of every industry. They are a powerful driver for economy wide productivity, growth and jobs-and are arguably Ethiopia's best investment for the future. [4]

Currently, as shown below, there is a lot of rail demand in Ethiopia. So by providing a full manufacturing technologies, it is possible to make the Ethiopian basic metal industries to expand themselves to produce a rail.

The Ethiopian Railways Corporation has identified eight railway corridors, the total estimated length with buffer of which is some 5065Km. The eight railway roots are shown in table below:

Table1. Railway Construction roots and their length. [3]

Root No.	Root Name	Length (Km)	Remark
1	Addis Ababa-Modjo—Awash-Diredawa-Dewanle	656	
2	Modjo-Shashemene-Arbaminch-Konso	905	
3	Adis Ababa-Ljaji-Jimma-Guraferda-Dima	740	Extend to South Sudan
4	Ljaji-Nekemt-Assosa-Kumruk	460	
5	Awash-Kombolcha-Mekele-Shire	757	
6	Fenoteselam-Bahirdar-Wereta-Weldiya-Semera-Elidar	734	
7	Wereta-Azezo-Metema	244	
8	Adama-Indeto-Gasera	248	
9	Addis Ababa LRT and Others unspecified roots	321	
TOTAL		5065	

To implement this 5065Km railway project, the amount of rail required is as follows:

The length of one rail is 12.5 meter. So to cover the length of 5065Km, it needs a minimum of rails. It is known that the railway construction project in our country will not be limited in the above root only. Although some of the rails for Addis Ababa LRT project are already imported, there is a demand of rail for future expansion of Addis Ababa LRT project. And if rail manufacturing factories are implemented within the country, it saves foreign currencies. Moreover, since most of African country don't have rail way infrastructure, so by exporting rail for them, our country can get foreign currencies. Therefore, localizing rail manufacturing has a lot of economic and social benefits for our country.

So the reason why I want to do my master degree thesis on “Roll Pass Design of UIC 60 Rail Using FEM” is to put my own contribution in localizing the manufacturing of the rail by providing an optimized rail roll pass design and in doing so, saving foreign currencies for our country and creating additional job opportunities for the citizens.

1.2. Statement of the Problem

Basic metal and engineering factories plays a great role in enhancing the economic development of the country. The value of metal processing as a development tool is based on the fact that they can help:

- to save foreign currencies which were used to bought those metal products and also getting additional currencies by exporting the metal products
- it creates additional jobs opportunities
- it promotes the development of other related industries like construction industries, raw material processing industries, and so on. And also it gives a chance to create many suppliers and whole sellers.

Over years the success of Ethiopian Basic Metals Industries to achieve the above objectives has limited due to difficulties of transferring the technology and getting a full manufacturing and process design, relatively a long payback period is needed, lack of raw material with in the country, relatively high investment capital is needed to implement such industries, shortage of power, shortage of foreign currencies and so on. However, especially in the last five years, the metal and engineering sector in Ethiopia is growing relatively faster and faster following the consistent economic growth of the nation results the fast development of construction industries as a result, the demand for metal and engineering products is increased. Though there

is a rapid development in the sector, the product obtained is still low in versatile of the product due to the fact that the basic metal and engineering industries are engaged in producing only a short list of metal product.

Ethiopia is engaged in building various mega projects. Like Grate Renaissance Dam, Railway Industries, Sugar industries, fertilizer factories, and so on. Due to this, there is a highly growing demand for metal and engineering products. And most of the metal and engineering products are imported and it costs a lot of foreign currencies. So it should be a big economical and development issue for our country to substitute these highly consumed metal and engineering products by improving the performance of the existing metal and engineering factories and by establishing new manufacturer industries.

The main problem of establishing rail manufacturing industry is getting a full manufacturing & process design and transferring the technology. So this thesis is focus to solve this problem by designing an optimized roll pass for a rail and by doing so, local metal product factories are initiated to expand themselves to manufacture rail. Due to that the demand of rail will be fulfilled locally and also it can be export to other countries.

1.3. Objective of the Study

1.3.1. General objective

The general objective of this study is to transfer roll pass design technology so that local steel mills can in the future produce rail section.

1.3.2. Specific Objective

The aim of the thesis is to validate the developed model in order to use it for different ways:

- to review the rail sections used in practice
- to review and acquire design technology of roll pass design
- to generate preliminary design of roll pass that can be optimized by conducting thermos-mechanical analysis
- to conduct thermo- mechanical analysis under plasticity condition using DEFORM 3D that uses nonlinear stress analysis

1.4. Significance of the Study

The study will help to:

- Reduce cost of tools during manufacturing of rail
- Minimize the trials in the design of the rolls
- Reduce the material waste during manufacturing of rail
- Increase confidence in the manufacturing of rail
- Improve quality of the final rail product
- Lower overall manufacturing cost
- Improve the productivity and market share of local long rolled product manufacturing factories by increasing the versatility of their product

1.5. Scope and Limitation of the Study

This thesis cover only the finite element analysis of the optimized roll pass for UIC 60 rail which is standard and widely applicable types of rail. And the analysis is performed only using the DEFORM 3D software. The analysis of the cooling and straightening of the rail after rolling is not included in this thesis.

1.6. Methodology of the Study

The following methodologies are used to conduct the thesis

- i.** Literature review and survey of previous relevant publishing, newspapers, journals etc.
- ii.** Primary and secondary data which are needed for the study are collected using different data collection techniques.
 - From a respective private and government office like metal industry development institute, Central statistical agency, Ethiopian custom and revenue authority, walya steel industry etc
 - Interviewing concerned bodies and companies (from metal development institute and waliya steel)
- iii.** After collecting and organizing the data, analysis is done
- iv.** After analyzing the relevant data and observing the different journals, literatures, etc, numerical analysis will be followed and then will simulated by using the finite element method (**DEFORM 3D**)
- v.** And finally conclusions, recommendations and future work of the study are explained.

1.7. Thesis Organization

The work presented in this thesis aims to integrate the knowledge obtained from different literatures into a DEFORM 3D finite element software to simulate a UIC 60 rail. The contents of the remaining part of this thesis is organized as follows:

Chapter 2: Because of the complex nature of hot rolling design, a thorough understanding of available design and analysis methods and the conditions of their applications is extremely important in order to achieve high quality rolled products. This chapter gives a review of the existing theory and experimental work in rolling. It provides a comprehensive discussion of a number of different empirical and theoretical methods for roll pass design. Finite Element (FE) methods for roll design specially DEFORM 3D are also discussed.

Chapter 3: The law of rolling for pass design, factors affecting lateral spread, the design considerations during roll pass designs, the plastic deformation of a workpiece, the effect of the tensile stress on the deformation process, heat generation within a workpiece during hot rolling, frictional effect in hot rolling, factors to be considered during part selection for shape rolling and optimization of roll pass designs are discussed in this chapter

Chapter 4: FEM is an important tool to simulate and study hot rolling. In this chapter, the UIC 60 rail pass is designed and it is simulated using one of the finite element software called DEFORM 3D.

Chapter 5: in this chapter, the result of the DEFORM 3D simulation is extracted and the thermal effect and the mechanical effect of the simulation results are discussed.

Chapter 6: in this chapter based on the result of the simulation, conclusions, recommendation and future works are explained. Finally references and appendix are treated at the end.

CHAPTER TWO

LITERATURE REVIEW OF ROLL PASS DESIGN

A thorough knowledge of the material deformation in rolling is necessary in order to optimize the design of the roll pass schedule. Many authors have proposed for roll pass design which are based on the use of empirical design formulae and experimental rolling mill data. Specific details of the previous roll pass design work and some of the factors affecting hot rolling are reviewed in this chapter.

2.1. Review of rolling

The rolling process can be defined as a continuous process of plastic deformation for long parts of constant cross section, in which a reduction of the cross sectional area is achieved by compression between two rotating rolls (or more). In cold rolling the material is deformed at room temperature (but it can be slightly higher with heat dissipation due to plastic work) and in hot rolling the temperature is high (more than half of the absolute melting temperature). Another important distinction is made according to geometric considerations. Flat rolling is performed with cylinders: this is also the case for sheet rolling or strip rolling (in which the thickness is very small, of the order of millimeters or less), or slab rolling (in which the slab thickness is of the order of 0.1 m) and any intermediate situation. Shape rolling allows the production of more complex workpieces by using appropriate roll geometries: the cross section of the part can be a round, an oval, various beams, a rail, and so on.

For hot or cold rolling of any geometry, the desired reduction of cross-sectional area is too large to be feasible in one pass. The final deformation is progressively applied by using several stands so that several pairs of cylinders successively deform the same part. Traditionally, the initial material form for rolling is an ingot. Figure 1 gives a summary of the main rolling processes. [24]

In rolling, the billet is drawn into the roll gap by the friction between the plastically deforming billet and the rotating rolls. The reduction in the pass, or compression of the billet, is accommodated in spread and elongation. Spread is the metal deformation in the lateral direction, and elongation is the metal deformation in the direction of rolling. Thus, complex three-dimensional metal deformation takes place. Although spread may be only a fraction of elongation, the ratio between spread and elongation varies at each pass with the reduction, billet

and roll shape geometries, roll diameter, roll speed, roll surface finish, and the billet material and temperature. [23]

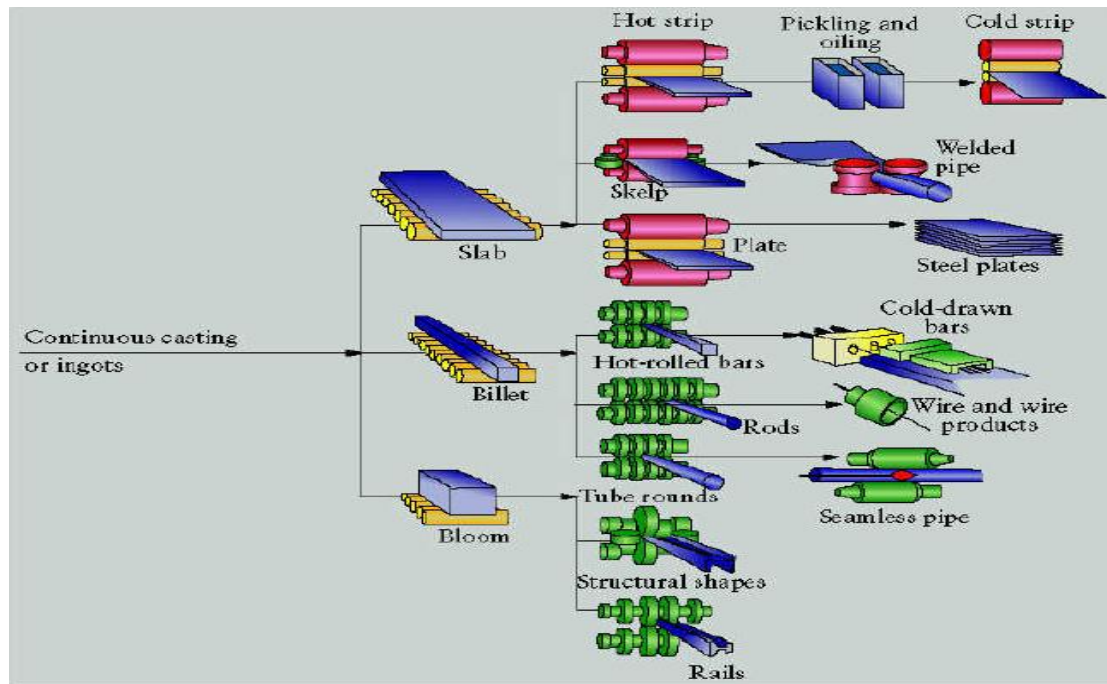


Figure 1: Schematic of various flat-and-shape rolling processes

2.1.1. Shape rolling

Shape rolling is one of the primary metal-forming processes. The process starts from blooms or billets, delivered from a continuous caster or a bloomery mill. After reheating, the stock passes through a succession of rolling stands. In each pass, the stock's cross-section is reshaped and reduced. After the final pass, the stock comes off the rolling mill in the form of a long bar. This gives the name “long products”, often used to refer a shape-rolling product. Significant for the shape rolling is the great variety of the profiles produced. Basic classification of the long products is shown in Figure 2. [15]

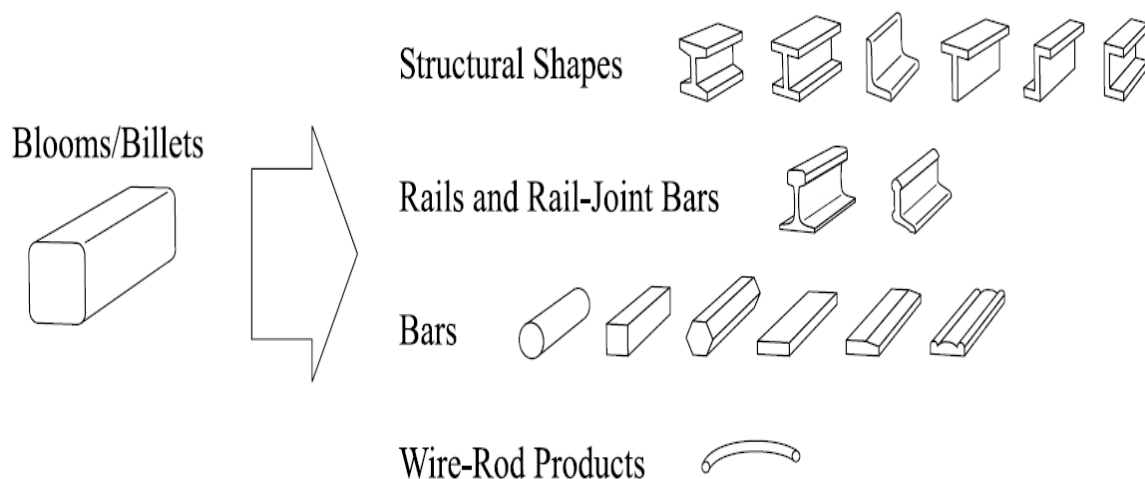


Figure 2. Classification of long products.

2.1.2. Structural and other Shapes

Shapes or sections as illustrated in Figure 3 are usually divided into two classes, structural and other sections. The former include such standard items as I-beams, channels, angles and wide-flange beams together with special sections such as zeers, tees, bulb angles and center sills (used in the building of railroad cars). Other sections include H-piles, sheet piling, cross ties and those used for special purposes. A number of processing steps are common to the production of all structural and other shapes. These include:

1. Heating the bloom,
2. Rolling to the proper contour and dimensions,
3. Cutting while hot to lengths that can be conveniently handled,
4. Cooling to ambient temperature,
5. Cutting to ordered length and
6. Inspection and shipping.

In some instances, the products are straightened and/or heat-treated by heating, quenching and tempering, care being taken to prevent distortion of the beam during the treatment. Shapes are furnished to standard section and length tolerances published by the American Society for Testing and Materials (Designation ASTM A6). The cross-sectional area or weight of each structural-sized shape shall not vary by more than 2.5 percent for the theoretical or specified value. Tolerances are established for variations in the cross-sectional geometry, the squareness of the ends and for the straightness of shapes (camber or sweep).

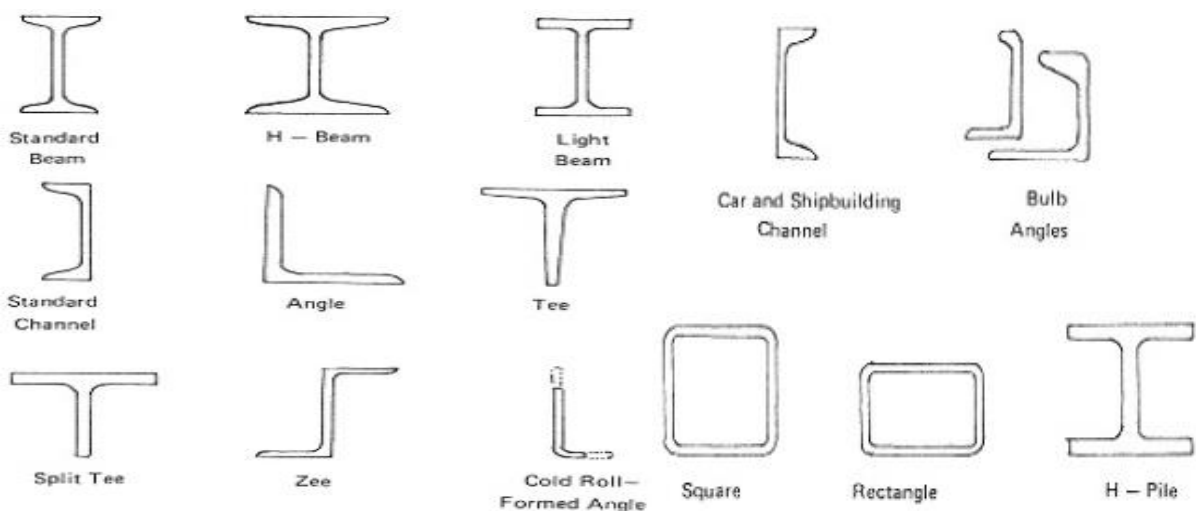


Figure 3. Cross-sections of structural and other shapes.

2.2. The Rolling of Rails

By definition, the standard rail is a section symmetrical about its vertical axis, which consists of three areas: head, web and base. The term tee is used to designate the general class of rail designs which resemble an inverted letter T, and to distinguish those rails, which are generally used in open-track construction, from girder and girder-guard rails which are usually embedded in pavements. Crane rails differ from standard rails in that they feature shorter, thicker webs, larger heads and thicker bases to withstand heavy, concentrated loads. For railroad applications, rails are rolled to sections up to 77 kilogram per meter although most rails made today are 70 kilogram per meter or less and are of the standard length of 12.5 meter. Practically all rail specifications are based on American Railway Engineering Association or American Society for Testing and Materials requirements. For various rail sections, typical compositions are as listed in Table 2, but small amounts of alloy steel rails have been produced for severe applications. Normally, the rail section is formed from rectangular blooms by a series of 10 passes. Roll passes must be carefully designed and the rolling operation properly supervised in order to meet the stringent dimensional and quality specifications. After rolling, the rails, with their complete identification hot stamped or rolled into them, are hot-sawn so that they cool to within 10mm of the desired cold length. They are then cambered (with the head on the convex side) so that they will be essentially straight at ambient temperature. Many rails are controlled cooled, being cooled normally on hot beds until their temperature falls to within the range 385 to 538°C. The rails are then charged into large insulated metal containers for a minimum of 10 hours. After cooling, rails are subjected to various finishing operations (straightening and drilling for joint bolts), inspected, the rail head chamfered in a grinding operation and the ends of the rail hardened.

Many rails are now heat-treated by a full oil-quench and temper, which hardens the entire rail section, or subjected to an induction heating operation which provides a surface hardening of the wearing surface of the head. However, with the use of chromium and molybdenum as alloying elements, rails are being conventionally produced with a yield strength of 1.38GPa and with a wear resistance equivalent to that of heat-treated rails.

2.2.1. Rails shape

During the history of railroad development, rail sections have evolved to the modern types as shown in Figure 4 with sizes ranging in weight from 32 Kg. up to and including 70 Kg. per meter with rails 30 Kg. per meter and lighter being classified as light rails. In addition, rails are

fabricated for use with cranes and for other purposes, some of these types being also illustrated in Figure 4.

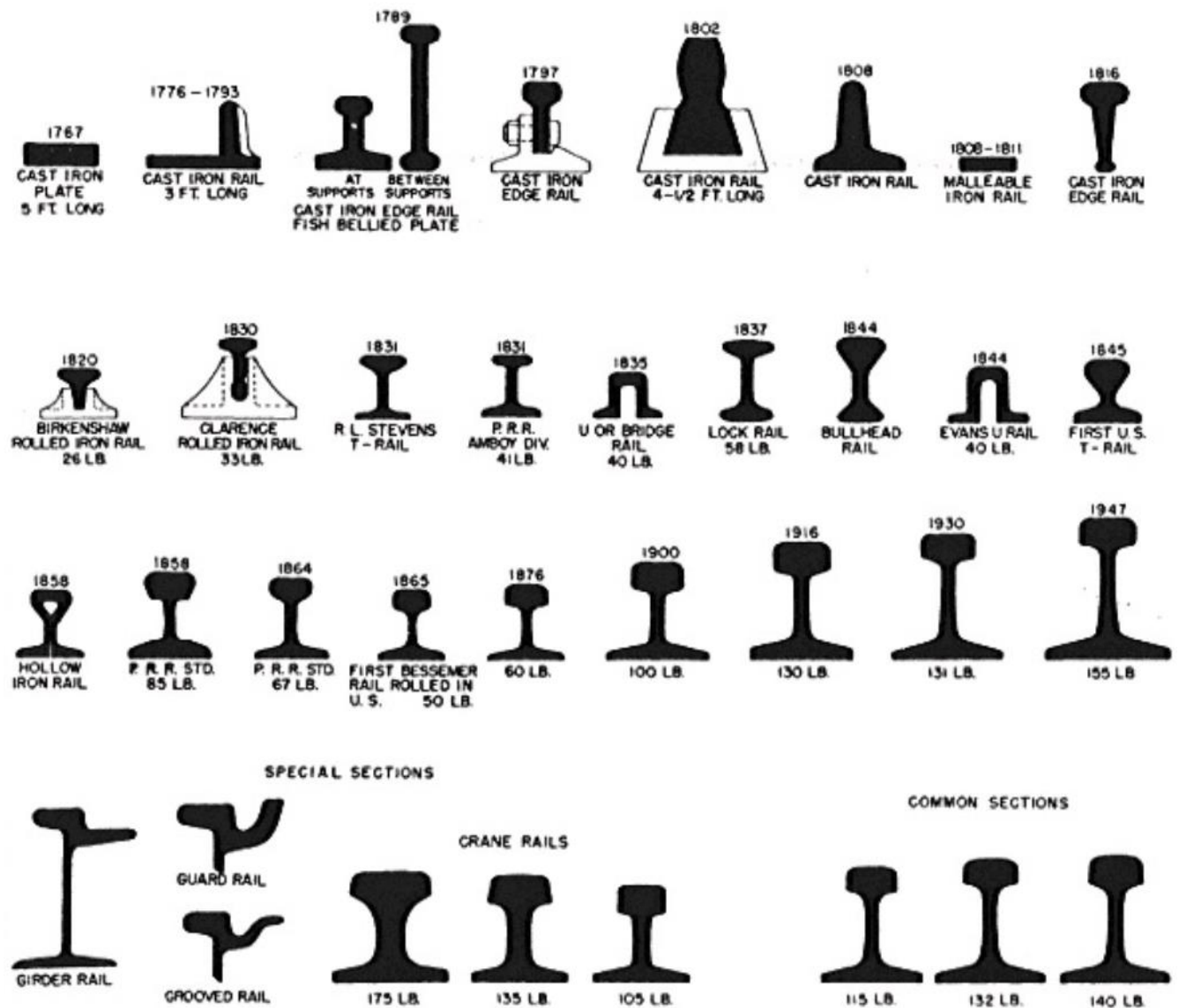


Figure 4. Cross-sections of various rails and the dates of their introduction

Typical compositions of rails are presented in Table 2. Starting with a bloom, rails are usually formed by two methods of rolling, namely tongue-and-groove, flat or slab-and-edging as well as the diagonal or angular method. Railroad rails must be cut to length (the standard length being 12.5 meter) when hot with accurately sawn ends and stamped with the heat number, ingot number and the position of the rail in the ingot. Prior to cooling, the rail is bent slightly so that its top surface is convex from end to end, an operation intended to compensate for the camber in the opposite direction normally occurring in the rails during carefully controlled cooling.[21]

Table 2: Representative chemical compositions for rail

Constituents	Nominal weight in Kg per Meter		
	40-45	46-60	61 and over
Carbon	0.640-0.77%	0.67-0.80%	0.69-0.82%
Manganese	0.600-0.90%	0.701%	0.701%
Phosphorus (Max.)	0.04%	0.04%	0.04%
Silicon	0.100-0.23%	0.100-0.23%	0.100-0.23%

2.2.2. Rail Strength

The use of alloy rail is not recommended to obtain the high-strength standards because of the additional complexities of welding alloy rail. Current standard and high-strength rail hardness, including the head hardening procedure, obtain the following standards:

- Standard Rail: 31.5 minimum Rockwell Hardness Number (HRC)
- High Strength Rail: 36.5 to 41.6 HRC (may be exceeded provided a fully pearlitic microstructure is maintained.)

2.2.3. Rail Metallurgy

The life of the rail can be extended by increasing the rail's resistance to:

- Wear
- Surface fatigue-damage
- Fatigue defects

Rail steel hardness, cleanliness, and fracture toughness can increase this resistance. The effect of rail hardness in resisting gauge face wear is a known fact. Increased rail hardness in combination with minimized sulfide inclusions reduces the likelihood of surface fatigue cracking. This, in turn, reduces development of subsequent defects such as head checks, flaking, and shelly spots. Oxide inclusion clean steel, combined with good fracture toughness, reduces the likelihood of deep-seated shell formations. Both shelly spots and deep-seated shells can initiate transverse defects, which ultimately cause broken rails.

The current rail standards include increased rail hardness and improved rail steel cleanliness, with the pearlitic steels peaking at 41.8 HRC. Recent research has focused on other structures such as bainitic steels. Although bainitic steels of the same hardness as pearlitic steel are not

as wear resistant, high-hardness low-carbon bainitic steel offers wear resistance superior to pearlitic steel. As a guideline for transit installations the recommendation is to install clean rail steel with a hardness of:

- 31.5-34 HRC (standard rail) in tangent tracks, except at station stops and severe profile grades greater than 4%.
- 40.8-41.8 HRC in tangent tracks at station stops, severe profile grades greater than 4%, curved track with radii less than 500 meters, and all special track work components including switch points, stock rails, guard rails, frog rails and rails within the special track work area.

These hardnesses may prove to be difficult to obtain in European girder rail sections. As a guideline, the girder groove rail should have a hardness of 31.5 HRC and greater. [25]

2.3. Review of Roll Pass Procedure

In flat rolling, as in the case of plate and hot-strip mills, the work rolls are basically cylindrical. However, in nonflat rolling, the cross-sectional geometry of the workpiece is established by the use of grooves cut into the pair of work rolls in each stand, these grooves being denoted as passes. Matching grooves made in both rolls of a set constitute an open pass, whereas a pass made by a projection on one roll fitting into a groove on the mating roll is called a closed or tongue-and-groove pass.

Passes of various designs are illustrated in Figure 5, the dotted lines showing the cross-section of the entering workpiece. Where both sides of the material in a roll groove are in contact with a different roll, the groove is designated a live hole. On the other hand, where a deep groove is cut into one roll so that material entering the hole is influenced little by the other roll, such a groove is known as a dead hole. Whereas in flat rolling the tangential speed is the same for each roll and very close to being constant across the roll face, in rolling with passes such cannot be the case. The bottom of a groove will exhibit a tangential speed less than a tongue so that forward slip will be different for different locations on the same cross-section. In nonsymmetrical passes, this can lead to a tendency for the workpiece to curl upwards or downwards, hence necessitating the use of stripper guides.

Several other facts should be noted about the design of various passes. In a box pass, perfectly parallel sides would lead to their excessive wear and difficulty in extracting the workpiece from the pass. Thus such passes are generally tapered by at least half to one degree.

Moreover, the pass must be designed, usually on the basis of experience, so that it is neither under filled nor overfilled. In the case of the former, the cross-section of the workpiece will be less than desired and surface irregularities will result. On the other hand, overfilling will create fins or projections on the sides of the piece which, if excessive, may result in damaged rolls and/or bearings.

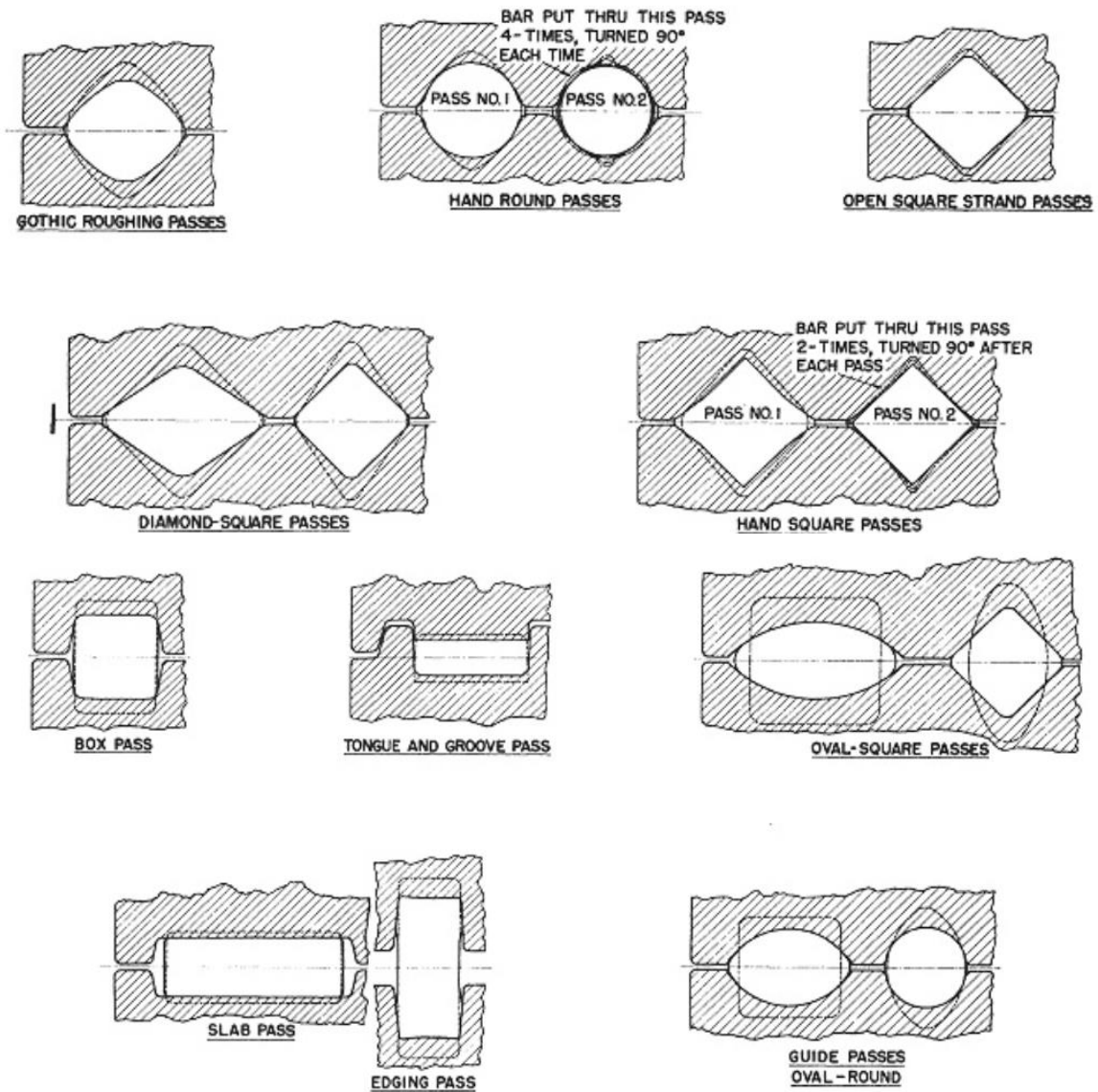


Figure 5. Common types of roll grooves or passes
(Dotted lines indicate cross sections of entering pieces)

Role pass design principles have been basically developed over decades through experience. Before 1980's, role pass design had been mainly based on empirical formula. A number of empirical formulae have been developed over the years, which vary in their functional character and applicability and are also different for ferrous and non-ferrous material. Most of

these formulae give good results only within a limited range. Some of the research formulations and roll pass procedures are reviewed below.

Sunil G. Janiyani and Prof. P. D. Solanki [34] designed a 17 roll passes for section rolling of flat footed rail section with the help Finite Element Analysis (Ansys). They explained the effect of percent reduction in cross-sectional area on the stress induced in the pass and also they explained the effect of angle of bite on the stress induced.

M. A. Guerrero, J. Belzunce, M^a C. Betegón [26] present the developed procedure for the simulation of the hot rolling process for UIC 60 rail. They also presented the thermo-mechanical characterization of the R260 quality steel, 0.7% C pearlitic steel, commonly used in rail rolling. A good agreement between FEM results and the sample shapes was obtained

S.-Y. Kim, Y.-T. Im [31] present a study of a three-dimensional finite element program for analyzing shape rolling processes considering heat transfer is developed based on rigid thermo-visco-plastic approach. Using the developed program, he simulated square–oval, round–oval, and square–diamond passes at different friction conditions with and without temperature effects. He also developed program that simulate a rolling of H-beam. And finally from simulation results, he investigate the non-isothermal and frictional effects on deformed shape, stress and temperature distributions of the workpiece, and forming loads.

Alejandro Rivera Muñiz [24] develop a fully nonlinear finite element analysis model that can be used as a tool in order to analyze the rolling of cold and hot steel strips under a series of different parameters and scenarios.

R. Lapovok and P. F. Thomason [16] provide the analysis to design roller which simplify the work of roll pass designer. They reduce the dependence of the designer on empirical experience and decrease the need for expensive and time consuming trial pass and groove design

C. Betegón Biempica [33] along with three of his partner study a paper that examine the residual stresses in an UIC-60 rail and their reduction by means of roller straightening. They also used the finite element method (FEM) to simulate one, two and three-dimensional analyses of a rail during roller straightening processes. The present model considers the longitudinal movement of a rail through the straightening machine, contact conditions between rail and rollers and kinematic hardening so as to take into account the plastic behaviour of the rail material (steel). They compared these results with the experimental investigations and good

agreement was observed. And finally, they proposed an improvement of the straightening process in order to obtain smaller residual stress in the rail section.

2.4. Hot Rolling Spread, Elongation and Draft

Elongation, spread and draft are important parameters which describe the three dimensional deformation of a workpiece in hot rolling. The early work of the theory of rolling has focused on two-dimensional deformation, where the ratio of the width to thickness of the workpiece is high i.e. > 10 and the spread of the workpiece 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. In this section, fundamental concepts of elongation, spread and draft will be discussed.

2.4.1. Elongation and Draft

Elongation and draft describe the two deformations in the directions of length and height of the workpiece. They are main parameters in the rolling process.

Definition of Draft

Figure 6 shows a flat rolling process. For the deformation of the parallelepiped of material shown in the Figure 6, draft is expressed as a linear reduction in height of the workpiece under the action of the compressive force.

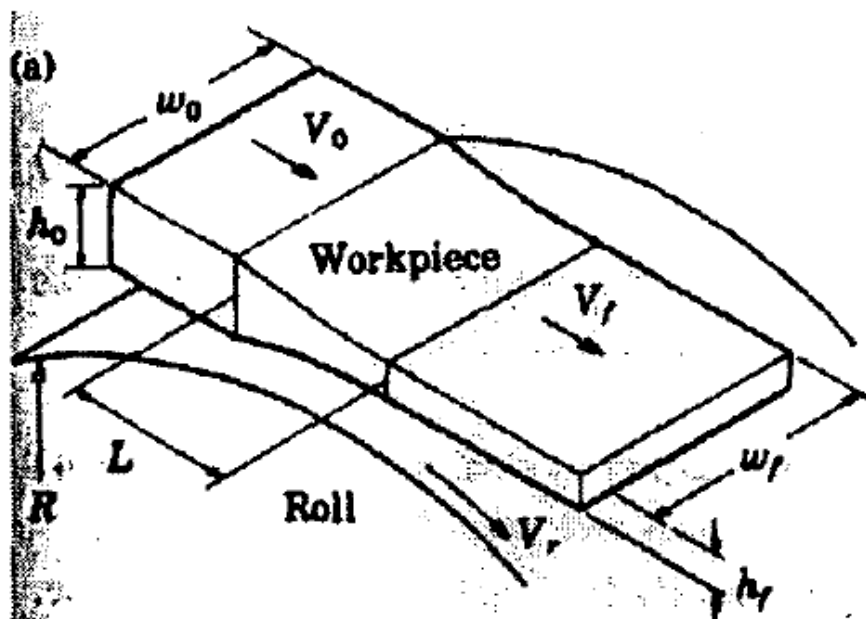


Figure 6. Flat rolling process

Definition of Elongation

In the theoretical analyses of plastic deformation processes, if the deformation of a parallelepiped is assumed, the volume of metal passing through the rolls remains constant, see Figure 6. Elongation is defined as the increase in length of the rolled material.

In the case of an irregular section the elongation coefficient is the most important design issue, which influences the whole rolling process. Elongation is used to determine the number of passes needed. In section rolling, one of the main tasks of the roll pass designer is to distribute the total elongation between each individual pass, based upon the number of passes that have been decided. In order to ensure correct filling of the next pass the mean elongation coefficient is needed.

2.4.2. Spread

The prediction of spread in rolling is mostly based on experimental observations. As a consequence a number of experimental investigations on spread have been carried out. Several formulae for the calculation of spread are discussed below. Other useful formulae are also listed and more detail can be found from the list of the references.

Definition of 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, see Figure 6. 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.

2.4.2.1. Classification of Spread and Filling

Spread can be classified into two types. The first is called free spread (unrestricted spread), for example, in the case of flat rolling where the workpiece passes through plain rolls. This unrestricted spread has a minor effect on producing elongation. The second type is restricted spread, which takes place in grooved passes. In this case the spread is smaller than for free spread. In restricting spread in section rolling, the edge of the work piece is compressed. However, if the spread is not correctly anticipated, it can result in over-filling or under-filling of the section. On entering the rolls the workpiece must be smaller in width than the grooves in the groove passes. Spread is thus restricted within certain limits. Over-filling means

excessive wear, and side thrusts on the roll collars, which is harmful. In under-filling the spread is not sufficient to fill the section and will not form the complete across-section shape.

Incorrect estimates of spread result in under-filling on one side and over-filling or fin formation on the other side. Fin formation must be avoided in all passes except the finishing pass, since it would be overlapped in edging and cause defects known as laps or seams. In the finishing pass, fin formation is permissible and sometimes unavoidable.

2.4.2.2. Factors Which Affect Spread

In roll pass design, the dimensions of groove width is determined from known spread formulae. This obviously indicates that spread is the most important factor that affects width control of the rolled product. Spread depends on many factors:

- **Pressure:** The workpiece is subjected not only to vertical pressure by the rolls, but also to horizontal longitudinal pressure. The greater this pressure, the greater spread.
- **Friction:** The higher the coefficient of friction, the higher the resistance to elongation and the more spread may occur.
- **Chemical components and microstructures:** Different chemical components and microstructures result in different coefficient of friction, which in turn influence spread. From empirical observations, spread of high carbon steel is greater than low carbon steel; the spread of alloys is greater than the spread of carbon steel.
- **Speed of rolling and temperature:** Within reasonable limits, slow speed favours spread, while high speed favours elongation. If the elongation of a workpiece is prevented by non-uniform plastic deformation distribution, the deformation will tend to go into spread.
- **Mill diameter:** Sometimes mill diameter influences spread. If bite area width increases, then spread increases.

Spread is a major research parameter for designers. It was observed as early as the beginning of theoretical analysis of rolling. Many of the early investigators attempted to consider the above factors simultaneously and to derive a general formula for spread but till now no such generally accepted formula exists. However, formulae have been developed for the determination of spread in flat rolling. Unfortunately, these formulae do not give sufficient accuracy when applied to practical rolling condition, because of the complicated nature of hot rolling i.e., their practical application is limited. Further, there is no theory of rolling to deal with 3D deformation. With few exceptions, studies on deformation in rolling have been largely

experimental. This means that prediction of spread in rolling has until recently remained mostly based on experimental observations. [19]

2.4.2.3. Review of future researches on spread

Review of some researches for spread during rolling are given below.

Ekelund [5] is the first researcher who developed a formula to find the spread after rolling empirically by taking variable as compensation constants but it can solve by successive approximation.

The other was Wusatowski [6] known by his book entitled “fundamental of rolling” made a study of the bar at the entry of rolls, and at the exit of the rolls. He collected his data from test carried out at various production mills. Based on the data and neglecting effect of the temperature, roll velocity, type and roll condition, and steel composition he later developed modified formulation by using some constant as correction factor for temperature, roll velocity, type and roll condition, and steel composition. He concludes that the theoretical economic limit is when the deformation produces equal spread and elongation of the bar.

Hill [7] studied Wusatowski’s formula and observed that the formula could not be fundamentally correct as it makes the variation of spread of passes with width to height or height to diameter ratio too rapid for small ratio. He also identified that the formula does not take into account the effect of draft and gives constant value of spread coefficient for different values of relative draft. Hill therefore suggested the corrected formula and according to him spread is primarily dependent on the ratio of initial width to the arc of constant.

Sparling [8] found that the existing formulae gave tolerable results only within the limited range of conditions for which they were empirically determined. He conducted tests on SAE 1015 at a temperature of $1100^{\circ}\text{C} \pm 5^{\circ}\text{C}$ with two different roll diameters.

He later modified his formula to allow for different rolling conditions by using correction factors which are little different from unity and allow for roll surface scale condition, material composition, rolling temperature, and mean strain rate during rolling. Sparling agrees with Hill about spread being primarily dependent upon the “width to arc of contact ratio” but says that it is secondary dependent upon the ratios width to height and roller radius to height. Later SPARLING together with EL-KALAY studied friction and its effect upon spread. Friction in hot rolling is affected by degree of scaling, roll surface roughness and the coolant. They found that smooth rolls always allowed a greater amount of spread than the rough rolls. Also spread

is not very sensitive to temperature, and the effect of scale on spread is independent of geometrical variables. However, the effect of roll finish on spread does depend upon geometrical variables-spread being highest for high reduction, smooth rolls and lowers width to height ratios. They used mean width and not maximum width in calculation of spread. The experiment was conducted at 1000⁰, 1100⁰ and 1200⁰C with rolls of 254 mm diameter by 254 mm length. [9]

Helmi and Alexander [10] conducted 217 test on steel having 0.18% C at about 1000⁰C and rolling speed of 0.1524m/s. They used a small two high, (152.4mm) barrel length. The roll gap was 12.7mm and average length of the specimen was 152.4mm. They compared the experimental results to those obtained using Wusatowski's, Hills, and Sparling's formula. Then they deduced that:

- Wusatowski's formula is in error as it does not allow for the effect of draft
- Neither Hill's formula nor Sparling's accurately predicts spread over the range of geometric variables considered in their investigation.
- Hill's formula gave excellent results for width to height ration of 2 but underestimated spread when width to height ratio of 1 and overestimated when the ratio is 4, while Sparling's formula gave good result up to a ratios of 4.
- For width to height ratio of 10 and 13 the difference between the predicted and experimental value was high.

Helmi and Alexander then develop their own formula which correct the above conditions.

J.G.Beese [11] performed industrial test to verify the reliability of the empirical formula by El-Kalay and Sparling, and by Helmi and Alexander on the spread prediction for wide slabs. Tests were conducted on both small and large slabs and these formula showed large errors for wide slabs. He then developed a new spread predicting formula based on the test results. The formula gave good results for values of width to height ratios of between 3 and 16 and for any rolling geometry having height greater than 12.7mm.

Shinokura and Takai [12] experimentally investigated the spread phenomena of steel rods in four types of passes to develop a new simple formula. The four types of passes included the square-oval, round-oval, square-diamond and diamond-diamond which are illustrated in the figure 7. A two high laboratory mill with steel rolls of 200mm diameter, five caliber or groove and roll speed of 14 rpm was employed. Mild steel bars about 200mm long where heated at 1050⁰C in an atmosphere of nitrogen and rolled without lubrication.

The profile of the side free surface differs for each type of pass. Geometrical approximation were made so that the profile of side free surface can be described mathematically and calculated with high accuracy. A close agreement was found between calculated and measured value. Then they developed a new spread formula. Later, it was proved that this new formula can be applied in other passes and to wide range of roll diameter, roll speed and temperature in both experimental and industrial practice.

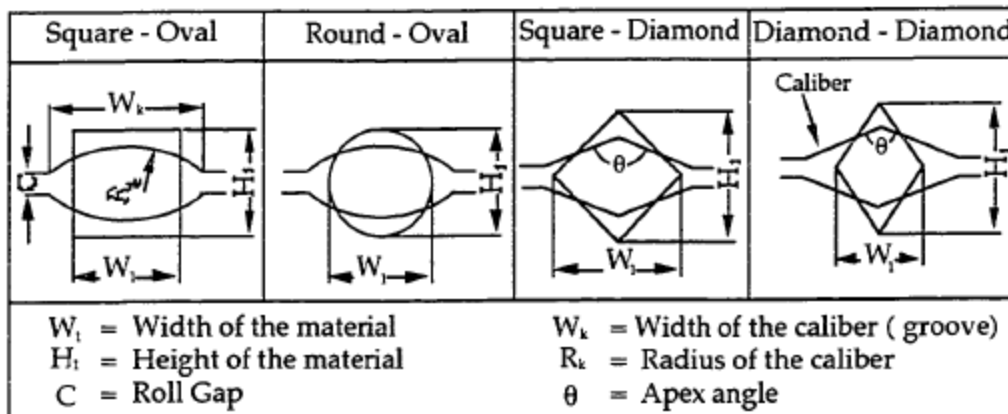


Figure 7. The four types of the passes Shinokura and Takai investigate the spread

2.5. Mathematical models of shape rolling

Mathematical models of the various hot-rolling processes are of considerable value to mill builders in the design of new facilities and to mill operators in establishing the capabilities of existing equipment to roll new materials or the same materials under different conditions. Because of the complexities and uncertainties involved in rolling operations, the development of mathematical theories has been largely restricted to two-dimensional models applicable to flat-rolling operations.

Based on everyday practice and extensive experimental work, the rolling engineers recognized that the main factors influencing the free spread of a material in a roll groove are:

- Shape of the groove, also called caliber
- Reduction
- Roll radius
- Friction
- Temperature of the material being rolled
- Rolling velocity
- Material being rolled and its chemical composition that influences the growth of oxide scale, which in turn influences the friction.

To predict these observations by means of mathematical formulations is a task all but trivial. Nowadays, there are basically two approaches to the mathematical modelling of shape rolling. The first, traditional, empirical approach in which relatively simple mathematical formulas have been derived in order to predict the global process parameters such as free spread, roll separating force and roll torque. Typically, the formulas contain sets of coefficients that approximate the effect of various rolling conditions. The approach can provide mean values of stress, strain and strain rate, experienced by the material in a rolling pass.

The second, up-to-date approach is based on numerical methods, mainly the finite-element method. Using the FEM, not only the global forces and displacements are successfully predicted, but also the local distribution of strains, strain rates, stresses and temperatures in the deformation zone of a workpiece can be followed. Obviously, the numerical approach is superior to the empirical one, but sometimes, its practical application may be hindered by its complexity and required computational power.

2.5.1. Empirical approach

The empirical methods are mainly applied for symmetrical rolling passes such as the round oval, square-oval and square-diamond passes. The obvious drawback of the empirical methods is that they apply correctly only for the conditions for which the models were evaluated. The advantage is that the models are fast and relatively simple to use. The practical significance of the empirical models is obvious. New models are still being developed and validated using either experiments or more advanced numerical models. [15]

2.5.2 Numerical approach

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 behaviour with thermal and viscous effects
- Time-dependent material behaviour 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.

2.6. Review of Computer-Assisted Roll-pass Design

Because of the complexity of the rolling process and the fact that there is no unique rolling sequence, computer-assisted methods for the analysis and design of the rolling process are being developed. Computer simulation of industrial processes is an important alternative to complement or to replace the expensive experimental procedures associated with innovative development. In the last 20 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 or rigid visco-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. The Finite Element Method (FEM) has made it possible to obtain accurate approximate numerical solutions. The FEM is now probably the most common technique used to investigate rolling problems, especially for section rolling.

According to Mottram 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. 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 2-dimensional continuum the Finite Elements may be triangles, a group of triangles, or quadrilaterals. For 3-dimensional analysis, the Finite Elements 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: [19]

- (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.

In early 1980's, many companies had computerized their roll-pass design procedures for rolling rounds or structural shapes. In Germany, CARD system (computer-aided roll design system) was developed at Aachen and introduced by Mauk et al. This system was composed of several modules such as mathematical material flow models, pass design models, etc., encompassing all the aspects from material flow calculations to graphic display. The main purpose of this system was to relieve the roll-pass designer of tiresome routine work as making drawings and control calculations, while leaving critical decisions to roll-pass design expert. For this reason, the system was merely a helping tool for roll-pass designer rather than designing tool and roll-pass design itself was still much dependent on the experience of roll-pass designers. [13]

Stanislav Riljak [15] applied the FE program namely called MSC.Marc for coupled thermo-mechanical simulations of wire-rod rolling. He predict the evolution of deformation and temperature in an AISI 302 stainless steel during hot rolling in a wire block. The experimental data are obtained by rolling of wire samples with an initial diameter of 25 mm and a temperature of 1000°C. The rolling was performed in the first four pairs of an industrial wire block with a round-oval-round-oval-round pass sequence. Then he analyses the evolution of temperature, strain rate and flow stress in the first four rolling passes of a wire block. He also evaluated an alternative approach to simulate shape rolling. He applied the approach is in order to save the computational time in cases where many shape-rolling passes are to be simulated. The approach was a combination of the slab method and a 2D FEM with a generalized plane-strain formulation. A number of various isothermal shape-rolling passes were simulated by applying the simplified approach. The simulations were carried out using an in-house 2D FE code implemented in Matlab. He then compared the result to fully 3D FE analyses. The comparison shows that the simplified approach can predict roll forces and roll torques with a fair accuracy, but the predicted area reductions are a bit underestimated. And finally he discussed the reasons for the deviations between the simplified approach and the 3D FEM are discussed.

Akgerman et al [14] developed two computer programs for modeling the shape rolling process for airfoil sections. The first program, SHAPROL, uses a modular upper bound method of analysis and predicts the lateral spread, elongation and roll torque. The second program, ROLPAS, simulates the rolling of relatively simple shapes, such as rounds, plates, diamonds,

ovals and airfoils using the slab method of analysis. The inputs to the interactive program ROLPAS are the geometry of the perform, the geometry of rolls, the flow stress of the rolled material, the friction factor and the variation of the elongation and spread in the rolling direction, as calculated by the program SHAPROL

In late 82's and early 90's, more hybrid or technology-integrated approaches were proposed by several researcher.

Jin et al. [17] has presented a 3D analysis of the rolling of the universal beam. The deformation analysis was carried out based on the upper bound theorem and a 3D continuous velocity field. The major factors that he taken into account are: (1) deformation of the web; (2) uneven distribution of the flow; (3) velocity in the lateral direction in both the flange and web deformation zones; (4) the special deformation mechanism of a wide flange beam in a universal pass; (5) flow between flange and web parts of the section; (6) and the roll separation forces.

Using a simplified 3D numerical approach, Shin et al. [18] presented a study in which the rolling of an I-section beam in the first four passes is analyzed numerically and experimentally. And he present the effective strain rate distributions for the right half of the billet. He finally proved that strain rates are concentrated at the center of the contact region.

Souvik Biswas [22] develop an off-line process model that can be used by engineers to expedite the optimum selection of process parameters in a high-speed mill for hot rolling of long steel products. The software tool developed in his work will help to predict the geometric properties of the hot rolled material. He provide a model to reduce manufacturing costs and shorten production cycle time while assuring product quality. He developed a coupled thermo-mechanical simulation model using the commercial finite element code ABAQUS. The rolling model is three-dimensional, thermo-mechanical, transient and nonlinear. He considered two case studies to demonstrate how the finite element model predicts geometric parameters which are necessary to satisfy customer requirements. The finite element model was validated through full-scale testing and verified with existing theoretical/empirical models. He finally demonstrate that the finite element model is able to predict geometrical properties to ensure that the steel mill satisfies the customer requirements.

In recent years, there has been substantial academic and commercial interest in making Finite Element analysis more accessible to non-specialist users. Finite Element (FE) software can meet most of the needs in industry. In application Finite Element programs use of the following processes:

i. Pre-processors

All of the tasks that take place before the numerical solution process are called preprocessing. The pre-processor software 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.

ii. Solvers

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 preprocessor, 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.

iii. Post-processors

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 colour. 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 a 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 makes ABAQUS a powerful tool to model problem-specific areas such as contact friction and interface heat transfer, which are vital in modelling the evolution of microstructure. However, the availability of user-defined subroutines is limited for the explicit formulation.[19]

Mirabile et al. [20] has compared eight different FE software package for the simulation of the rolling of hot flat and special sections such as beams and rails. This software includes: ABAQUS, DYNA3D, LAGAMINE, LARSTRAN, MARC, NIKE2D, PREFECT, and ROLL3 (DEFORM 3D). And he shows that these codes provide good agreement between experimental and predicted values of temperature, strain distribution, rolling forces and torques.

2.7. Review of DEFORMth 3D

DEFORM is a Finite Element Method (FEM) based process simulation system designed to analyze various forming and heat treatment processes used by metal forming and related industries. By simulating manufacturing processes on a computer, this advanced tool allows designers and engineers to:

- Reduce the need for costly shop floor trials and redesign of tooling and processes
- Improve tool and die design to reduce production and material costs
- Shorten lead time in bringing a new product to market

Unlike general purpose FEM codes, DEFORM is tailored for deformation modeling. A user friendly graphical user interface provides easy data preparation and analysis so engineers can focus on forming, not on learning a cumbersome computer system. A key component of this is a fully automatic, optimized remeshing system tailored for large deformation problems.

DEFORM-HT adds the capability of modeling heat treatment processes, including normalizing, annealing, quenching, tempering, aging, and carburizing. DEFORM-HT can predict hardness, residual stresses, quench deformation, and other mechanical and material characteristics important to those that heat treat

2.7.1. Capabilities of DEFORM 3D

Deformation

- Coupled modeling of deformation and heat transfer for simulation of cold, warm, or hot forging processes (all products).
- Extensive material database for many common alloys including steels, aluminums, titaniums, and super-alloys. (all products).
- User defined material data input for any material not included in the material database. (all products).
- Information on material flow, die fill, forging load, die stress, grain flow, defect formation and ductile fracture (all products).
- Rigid, elastic, and thermo-viscoplastic material models, which are ideally suited for large deformation modeling (all products).
- Elastic-plastic material model for residual stress and spring back problems.
- Porous material model for modeling forming of powder metallurgy products
- Integrated forming equipment models for hydraulic presses, hammers, screw presses, and mechanical presses (all products).
- User defined subroutines for material modeling, press modeling, fracture criteria and other functions (2D, 3D).
- FLOWNET (2D, 3D) and point tracking (all products) for important material flow information.
- Contour plots of temperature, strain, stress, damage, and other key variables simplify post processing (all products).
- Self contact boundary condition with robust remeshing allows a simulation to continue to completion even after a lap or fold has formed (2D, 3D).
- Multiple deforming body capability allows for analysis of multiple

deforming work pieces or coupled die stress analysis. (2D, 3D).

- Fracture initiation and crack propagation models based on well known damage factors allow modeling of shearing, blanking, piercing, and machining (2D,3D).

Heat Treatment

- Simulate normalizing, annealing, quenching, tempering, and carburizing

2.7.2. Analyzing Manufacturing Processes with DEFORM

DEFORM can be used to analyze most thermo-mechanical forming processes, and many heat treatment processes. The general approach is to define the geometry and material of the initial workpiece in DEFORM, then sequentially simulate each process that is to be applied to the workpiece.

The recommended sequence for designing a manufacturing process using DEFORM are:

- Define your proposed process
- Final forged part geometry
- Material
- Tool progressions
- Starting workpiece/billet geometry
- Processing temperatures, reheats, etc.
- Gather required data
- Material data
- Processing condition data
- Using the DEFORM pre-processor, input the problem definition for the first operation
- Submit the data for simulation
- Using the DEFORM post-processor, review the results
- Repeat the preprocess-simulate-review sequence for each operation in the process
- If the results are unacceptable, use your engineering experience and judgment to modify the process and repeat the simulation sequence. [27]

2.8. Defects in Rolling

During rolling, if the parameters are not carefully designed, the rolled object will have a defect like cracks and scratches, fins and laps, corner cracks and porosity. Each of the defects are discussed in detail below

2.8.1 Cracks and Scratches

By experience, the most common defects in bars are cracks and scratches. Cracks can be caused by improper roll-pass design, damaged roll surfaces, worn out grooves and coarse scale rolled into the surface of the rolled product. Cracks can be found at any point in the production line from steelmaking to finished product. Because of the elongation during rolling, cracks formed in the early stage of processing will elongate during the later. Cracks can be detected with the naked eye or at a low magnification after the surface of the bar has been chemically or mechanically rescaled.

2.8.2 Fins and Laps

Due to improper roll adjustment, overfilling may occur in one pass. Then in the next pass, the overfilled region passes a roll-groove bottom, folds and is rolled into the surface trapping a double oxide layer just beneath the rod surface. The folded material is recognized as “fins” or “laps”.

The reason for forming laps is that the bar is simultaneously gripped by many rolls and normally stretched. At the ends, the stretching disappears and the bar becomes thicker overfilling the roll gap with the formation of laps. However, laps can also be formed when the roll-pass is not adequately filled or when the guides are badly aligned. Poorly filled parts of the cross section can then develop into laps in the next roll pass. Often, it is difficult to distinguish laps from defects of similar appearance like shells, scratches or scoring.

2.8.3 Corner Cracks

Some forms of surface cracking are caused by a combination of limited ductility and high stress concentrations. These cracks are transversely oriented, usually appearing on the corners of a billet but may extend appreciably along the sides. Many high-alloy steels have an inherent low ductility and are particularly prone to such corner cracks. Strict control of stock composition and re-heating conditions can reduce the severity of corner cracking.

2.8.4 Porosity

The finishing rolling-speed for rolling rod has successively increased up to 100-140 m/s. Such a high rolling speed generates a high temperature rise and high strain rate in the wire rod in a short time. This causes a risk of partial melting at grain boundaries in the material leading to defect problems such as porosity, for instance.

2.8.5 Defects from Improper Roll-pass Design

During rolling strains and heat are accumulated which may result in the development of defects. Just as an improper roll-pass design may initiate and increase the defect size during rolling, a proper design may reduce the defects, and in the best case, even eliminate them. A study of a diamond-square and a square-oval pass has shown, that the most efficient method for eliminating an artificial surface crack is to design the roll-pass for a material flow in the radial direction opening up the crack in the angular direction. [29]

CHAPTR THREE

GENERAL CONSIDERATIONS of ROLL PASS DESIGN

Before starting the design of roll pass for rail, first it has to understand the general considerations of roll pass design. Therefore, this chapter describes about roll passes and their properties in shape rolling, common roll pass designs, properties of different pass sequences, break down systems for rolling of simple square profiles, independent parameters defining the form of the pass, law of rolling for pass design, factors affecting lateral spread, design considerations during roll pass designs, the plastic deformation of a workpiece between two platens, the effect of tensile stresses on the deformation of a workpiece of rectangular cross-section in a roll bite, energy requirements in non-flat rolling, optimization of roll pass processes and finally the cooling and descaling of workpiece.

3.1. Roll Passes and their properties in Shape Rolling

Process sequence design of shape rolling consists of roll-pass design and profile design, which will enable a simple rectangular billet to be transformed into a final round shape. In general, sequence design relies on empirical rules or the know-how of design engineers, requiring costly effort at the development stage. Therefore, many studies have been carried out, experimentally and numerically, on shape rolling for better design.

In many commercial bar rolling mills, the prime concern is to produce an appropriate cross sectional shape and area rolling as quickly as possible and using as few passes as possible in order to increase market satisfaction and productivity. Dimensional accuracy and quality of the bars are very important, since these bars are normally used directly in many applications. It is thus impossible to accept products with any marks, scratches, shells, cracks, overfills or oxide particles on the surface.

Nowadays in the steel industry, demands on quality, dimensional tolerances and mechanical properties of the rolled products are increasingly becoming more rigorous. Passes in shape rolling are divided in to two main categories based on the orientation and size from the x and y axis to the surface of the groves.

- i. **Definite Passes** – those having two equal axes in an x, y plane (example square groove, round grove).

- ii. **Intermediate Passes-** those having one axis larger than the other one (Rectangular-box, diamonds, oval)

When a definite bar passes in to intermediate pass or an intermediate bar in to definite pass configures a deformation consequently axial elongation will be formed.

Intermediate pass sequence can be broadly categorized in to three types. These are:-

a. **Breakdown Passes:** these are used for reducing the cross sectional area nearer to what is desired. These would be the first to be present in the sequence. The principal breakdown pass sequences are:

- **Box pass series:** are generally used for initial medium and large sections of billet mills. The rolls of box pass series are stronger. They can be used for different sizes by screwing down the top roll. They provide for effective rescaling and ensure uniform elongation along the width of the bar. However the main problems with these are the smaller elongation (1.05-1.15) and inaccurate square produced because the side spread is not controlled. It is largely used for continuous long products.
- **Diamond-square series:** in this, the square produced in a larger roll is turned over by 90° and put through smaller square rolls. The advantages of this series are the slow cooling of entire material, accurate squares that are possible and larger elongations that can be achieved (1.2-1.45). Because of these specific advantages, these are extensively used in the finishing process of the comparatively smaller sections such as billets. The material being confined fully, these type of passes give a good stability and also uniform deformation of the material. The two principles that are generally used in designing the diamond-square series is to keep the height of one pass equal to the width of the next pass or the height of one pass is less than the width of the next pass. The disadvantage with the series is that the roll gets weakened because of the deep impressions made into the rolls.
- **Oval-square series:** In this series the diamond is replaced by oval shape. The stock after going through the oval pass is turned over by 90° into the square pass, the output of which is then turned over by 45° to feed in to the next oval pass. The main advantage of this series is the larger elongation that can be obtained (1.35-1.8) compared to the other breakdown passes. The main problems of this are the difficulty to guide the stock in oval pass, the non-uniformity of the deformation along the width of the roll and higher roll wear in oval pass. When higher reductions are used, the

material is likely to give rise to surface called ‘fold’ because of the wearing of the oval pass at points of maximum reduction, which cannot be eliminated.

b. Roughing Passes: in these passes also, the cross-section gets reduced, but along with it, the shape of the rolled material comes nearer to the final shape. The most common pass design sequences used in roughing passes are “square-oval” and “false round (round)-oval”. It is also common to use “diamond-square” and “diamond-diamond” sequences upstream in the rolling mill. In the roughing mill, also box grooves are common. The characteristics of the square-oval and false round-oval sequences are shown in Figure 8.

False round-oval series are very popular in continuous mills. The reason is that the series are gentle to the bar and have high flexibility. The reduction capacity is lower than for square-oval series and is usually about 17% per pass, but can be considerably higher when using flat ovals.[29] Twisting of the bars is eliminated in this series by arranging the stands in alternating horizontal and vertical position. It could be mentioned that roller guides are needed for guiding the oval bar into the false round grooves, see Figure 8 a, b.

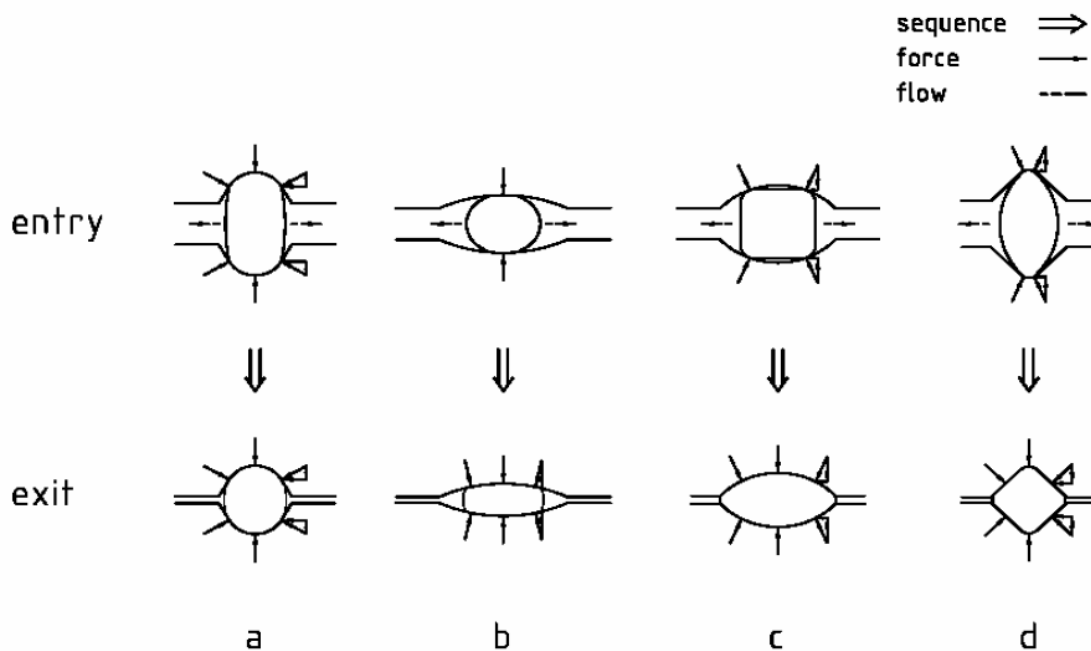


Figure 8: Common sequences in bar rolling: a) oval-false round, b) false round-oval, c) square-oval and d) oval-square

The square-oval series are stable and have a relatively high reduction capacity. Average reduction is about 25% per pass. The “square” is twisted 45° before entering the oval groove. After reduction, the “ovals” are turned 90° before entering the square groove. This series is not recommended for rolling of heavy sections. When a “square” is twisted 45° before entering the

oval groove, they can become distorted. In addition, the corner of the “square” is too sharp to fit in the oval groove, and because of that, the oval grooves are worn out very fast causing high cost and extra downtime for roll replacement. Normally, rollers guides are used to stabilize the oval bars before entering the square grooves, see Figure 8.c, d.

Diamond-diamond, sequences have lower reduction capacity than the square-oval series, about 20%. The series are stable and commonly used in roughing mills where the bite angle is large. Even problems with uneven bar temperature distribution can arise. The corners of the bar are cooling down much faster than the bar sides and center causing a risk for corner cracks due to high tensile stresses.

c. Finishing Passes: these are the final pass which gives the required shape of the rolled section. Generally the finishing pass follows a roughing pass.

3.2. Common Roll Pass Designs

Roll pass design is an important field of rolling mill technology. In bar and wire rod rolling using grooved rolls, the cross-sectional area is reduced and the bar is elongated with large lateral spread. The function of roll pass design is to ensure the production of the desired shape, good surface without any defects and at the lowest possible cost. A good series of grooves must guarantee stable rolling [29]. The function of the grooves is to reduce the cross-sectional area and elongate the bar efficient, i.e. with a low amount of spread. Common grooves are rectangular box grooves, diagonal grooves such as squares and rhombic grooves (diamonds), and round or false round grooves as well as oval grooves. In production, a combination of grooves is named, “pass design” of “groove series”. An entry bar rolled in a groove to an exit bar is defined as a “sequence”. A “series”, means a schedule of sequences built up by two or more “grooves”. Table 3 shows different combination of rolling sequences. [32]

Working range or flexibility for grooves normally means the possibility for a single groove to deliver a bar with well-defined shape from a given entry section. For a series of grooves, the working ranges for the single grooves are connected and inter linked with each other in the pass design.

A good pass design must guarantee stable rolling and with optimum running time. The bar must be easy to guide, to reduce the risk for surface scratches, hobbles. It is an advantage to use the same intermediate grooves for many final dimensions

Table 3. Combination of rolling sequences for an entry bar rolled in a groove to an exit shape.

Entry bar → Exit bar ↓	Flat/Box	Oval	Edge oval	Diamond	Square	False round	Round
Flat/Box	Used	Possible	Used	-	Used	Possible	Possible
Oval	Used	Used	Used	-	Common	Common	Common
Edge oval	Used	Used	-	-	-	Possible	-
Diamond	Used	Used	-	Common	Common	Possible	Possible
Square	Possible	Common	-	Common	-	-	Possible
False round	Used	Common	-	-	-	-	Used
Round	Used	Common	-	-	Possible	Possible	-

Key:-

- *Common: widely applicable.*
- *Used: possible to use.*
- *Possible: possible but not much applicable.*

3.3. Properties of Different Pass Sequences

The reduction capacity of different roll-pass series is presented in a work of Collin. Common average reductions, for some sequences used in industry are shown in table 4

Table 4: Common average reductions for some common series

Series	Average area reduction (%)
Square-oval	25
False round-oval	17
Round-oval	20
Diamond-square	24
Oval-square	30-35 (maximum) [10]
Gothic-Square	12-15
Box-Passes	20-25
Diamond-Diamond	12-15

Limits for the square-oval series are the fitting of the oval edges into the square groove bottom. The ratio of width over height of the oval should be in the range of 1.5-3.5. A quite sever limit

is that the ratio of diagonal length of the square should be in the range of 0.95-1.05. Otherwise the rolling in the following oval will be unstable.

3.4. Breakdown Systems for Rolling of Simple Square Profiles

In the following section, the major advantages and deficiencies of five common systems for breaking down square profiles is given. Passes of simple form, such as box, square, oval, diamond etc. are usually used in rolling of simple profiles, like a square profile. Breakdown systems for producing square profiles include the sequences [16]:

- i. Right angle-square (box),
- ii. Diamond-square,
- iii. Diamond--diamond,
- iv. Oval-square,
- v. Hexagonal-square,

Each of which has advantages and deficiencies which have to be considered in choosing the breakdown system and these have led through experience to restrictions on the values of geometrical parameters which should be taken into account in the optimization procedure.

3.5. Independent Parameters Defining the form of the Pass

The geometrical parameters characterizing the form of each pass used in the above breakdown systems are given below which identifying relationships between those which are not independent and restrictions on those values which have already been established by experience.

In the design of the form of passes, it is necessary to know such parameters as height and width of the pass (in open passes), depth and width of roll grooves and the radii of the root and shoulder of the grooves, the width of the bottom of the groove for a box pass, radius of curvature for an oval pass, magnitude of clearance, etc.

The parameters may be divided into two groups, those which are independent and can be freely varied by optimization, and those which are restricted by relationships based on experience (or are defined by geometry). For every type of pass we can choose independent parameters defining the form of the pass and which can be changed to optimize rolling. We may also

distinguish between principal parameters defining the form of the pass and secondary parameters associated with detailed design.

B_p = width of roll groove

H_1 = is height of pass (equal to the height of the billet after rolling)

$S = (0.01 - 0.03)D$ for initial passes

$S = (0.005 - 0.01)D$ for final passes

Where

D is the diameter of the roll.

The need for a compromise between maximizing elongation in a given pass and securing stability of the section during rolling suggests values of the ratios, $a_p = \frac{B_p}{H_1}$ of the lengths of the axes of the groove derived from empirical experience.

- For Box-right angle pass $a_p = 0.5 - 2.5$
- For Square pass $a_p = 1$
- For Diamond pass $a_p = 1.2 - 2.5$
- For Oval pass $a_p = 1.5 - 4.5$
- For Hexagonal pass $a_p = 2.0 - 4.5$

Another important characteristic is the degree of pass filling, $\delta_1 = \frac{B_1}{B_p}$, in which B_1 is given and B_p can be varied freely within the ranges specified as follow. Although the nominal maximum value of δ_1 is $\delta_1 = 1$, overfilling starts in the majority of passes with smaller values of δ_1 , so that in practice values of δ_1 ($\delta_1 < 1$) are usually used; $\delta_1 = 0.8-0.9$ for oval, square, diamond and hexagonal passes; $\delta_1 = 0.85-0.95$ for box passes.

The limits, formulae and restrictions mentioned above have to be included in the variation of the rolling parameters.

3.6. Laws of Rolling for Pass Design

First Law: The purpose of the rolling process is to start from a relatively short bar with a relatively small section area, aiming to obtain a very long product. Then, the first law to remember is that the volume (or the weight) is a constant: from a ½ ton billet we will obtain a ½ ton bar. Therefore, cross sectional area times bar length is a constant.

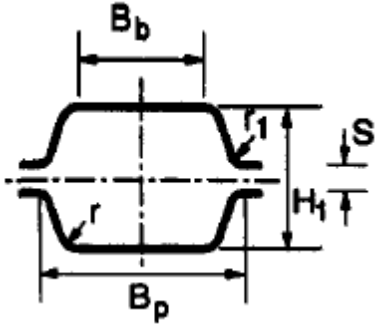
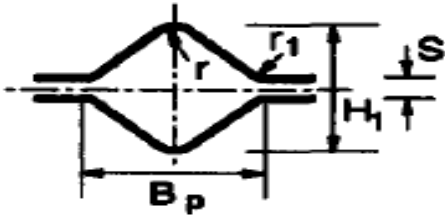
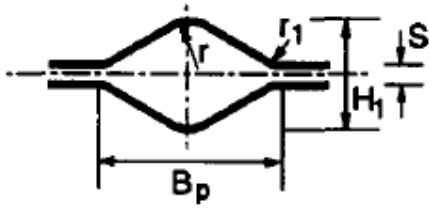
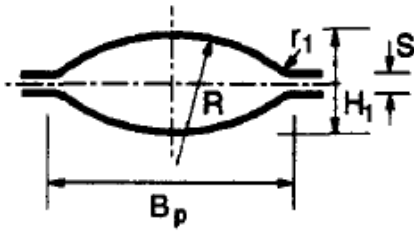
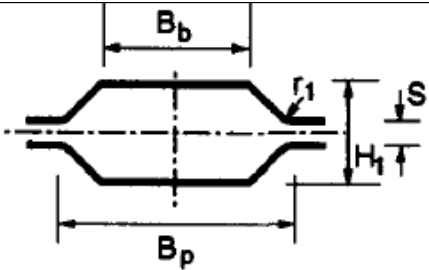
Second Law: There is another, important law to remember: the flow is also constant. For example the exit bar from stand 1 has cross sectional area=3467 sq mm and the finished round

has cross sectional area=113 sq mm. If the finished stand delivers at a speed of 12 m/s, then stand 1 must 'run' at 0.39mps: $0.39 \times 3467 = 12 \times 113$. In this case the constant is about 1356, i.e., if we know the areas, we have no problems in setting the speed at each stand, as each stand has its own independent motor.

Third Law: the law of reduction and elongation

- i. Reduction (with a coefficient of reduction gamma) –is defined as ratio between exit and entry height is always less than one.
- ii. Elongation (with a coefficient of elongation Lambda) –is defined as ratio between exit and entry length, but more often as ratio between entry and exit section area is always greater than one.
- iii. Spread (with a coefficient of spread Beta) –is defined as the ratio between exit and entry width and is normally greater than one. The rolling process can be systematized by one equation: $\beta * \gamma * \lambda = 1$. which is a mathematical way of saying that the volume is a constant.

Table 5. Empirical formulae for some of the common passes

S.N	Pass Name	Important Parameter	Formulae	Remark
1	Square-box pass		$Area = H_1 (B_b + B_p)$ $B_b = (0.95-1.00) B_p$ $r = (0.1-0.15) H_1$ $r_1 = (0.8-1.0) r$	
2	Square pass		$Area = B_p \times H_1$ $H_1 = B_p$ $r = (0.1 - 0.2) B_p \frac{\sqrt{2}}{2}$ $r_1 = (0.1-0.15) H_1$	
3	Diamond pass		$Area = B_p \times H_1$ $r = (0.1-0.2) H_1$ $r_1 = (0.1-0.15) H_1$	
4	Oval Pass		$Area = \frac{\pi B_p * H_1}{4}$ $r_1 = (0.1-0.4) H_1$ $R = H_1 \left[1 + \frac{B_p^2}{H_1^2} \right]$	
5	Hexagonal pass		$Area = H_1 (B_b + B_p)$ $B_b = B_p - H_1$ $r = r_1 = (0.15-0.4) H_1$	

3.7. Design Considerations during Roll Pass Design

Roll design usually proceeds in the following manner. From a template of the desired section, a hot template is constructed corresponding to the section during finish rolling when the dimensions are about 1-1/2 per cent larger than at ambient temperature. Having decided on the initial billet or bloom size, the roll designer specifies the intermediate passes, establishing a construction line or pitch line which locates the center of gravity of the section and which is usually positioned midway between the axes of the two work rolls. In creating the various passes, the designer must bear in mind the following considerations:

- The shaping of the workpiece will be accomplished by squeezing, spreading and bending,
- The reduction given by the various passes should be reasonably uniform except for the last pass where the shape is basically trued up,
- All sides or portions of the shape should be thoroughly worked,
- The workpiece should not enter two successive passes in the same position so as to avoid the development of fins,
- Deep cuts should be avoided so as to prevent weakening of the rolls,
- The passes should be shaped so as to avoid the side thrusting of the rolls as much as possible,
- The dimensions of the passes must be carefully controlled and the entering workpiece must not be larger than the pass in all dimensions, except in the case of diagonal rolling,
- Since the thinner portions of the shape cool faster than the thicker parts, the former should be developed in the later passes,
- Relatively deep grooves pose rolling difficulties because of the difference in peripheral speeds corresponding to the top and bottom of the groove, which may, in part, be resolved by using rolls of slightly different diameters, by raising or lowering the center of gravity relative to the pitch line or by decreasing the amount of reduction on the part that elongates more rapidly,
- The draft on the various parts of the section must be properly proportioned as otherwise the workpiece will be distorted,
- The different flow characteristics of the various grades of steel must be taken into account and
- The throughput of the mill should be maximized to the extent practical.

Once the passes have been designed, one or more hot templates are made for each pass. These templates are to be used in turning the rolls for which a special set of tools may be required. Great care is exercised in the roll shop so that the passes are exactly aligned on the two rolls. After a set of rolls has been in service for some time, the passes become so worn that they no longer produce the section to the desired dimensions. In most cases, these worn rolls may be turned or dressed again to produce a section of the original size or, if this is not possible, a section of similar shape but of larger dimensions.

In the case of two-high reversing blooming mills, blooming passes are considered as simple passes (except for shaped blooms). Rolls for such mills have slight collars separating the passes in order to control the sideways spread of the workpiece. To prevent the collars from cutting into the steel and thus forming laps, all the passes except the finishing are given a slight belly. A fillet at the base of the collars serves to keep the corners of the workpiece well rounded. In addition, to increase the bite of the mill, the rolls are usually ragged. In rolling some special steels, it is often the practice to turn the steel on each forward pass to avoid any possibility of forming laps and seams. Where sharp corners are necessary, extra passes may be given to produce the desired cross-sectional geometry.

In the case of three-high rolling mills, peculiar difficulties are encountered in pass design. First, in order to avoid weakening the rolls, only a small number of passes (about nine) are used. Second, this implies fairly large reductions per pass. Third, in order to achieve the greatest possible number of passes per set of rolls, the grooves must be placed one above the other so that a given groove on the middle roll must serve for both an upper and a lower pass. Fourth, the peripheral speed of the rolls at the base of the groove in any two rolls forming a pass must be approximately equal so as to avoid turn-up or turn-down. [21]

In shape rolling, prediction of deformations such as spread, elongation, and draft, pressure distribution between rolls and the workpiece, and forming load is important in designing proper roll grooves and pass sequences. Since initial temperature of the workpiece is in the range 1100–1200°C, temperature distribution of the workpiece is a significant factor which influences the mechanical properties due to variation of microstructure in rolled products. Thus, variation of the workpiece temperature distribution during shape rolling should be considered at the design stage.

In shape rolling process, the billet is formed through several roll passes with different roll groove shapes. To improve production efficiency and product quality, process designers must

optimize the amount of elongation at each roll pass and roll groove shapes. Since such design characteristics are dependent on material flow through roll grooves, stress and strain distributions of the billet, pressure distribution between rolls and the workpiece, and roll separating force must be considered in the process design for shape rolling. However, these factors are related to various process variables such as the shape of roll grooves, flow characteristics of the material, friction coefficients between rolls and the workpiece. Thus, process design for shape rolling is highly dependent on the experience of designers and empirical rules based on numerous experiments. However, such empirical rules are mostly focused on flow mechanism of the billet such as resulting spread and elongation for various roll groove geometries without considering the effect of various process variables and material properties.

In particular, in shape rolling, the billet is initially heated up to 1200°C , so heat transfer occurs at the rolls–billet interface and between roll passes. Thus, it is very important to properly predict heat transfer in the billet because the change of microstructure depending on temperature will affect flow characteristics of the material, roll pressure, and roll separating force. Therefore, numerical analysis of the process is adequate to reduce the number of trial and-errors at design stage and to consider the effects of processing variables such as stress, strain, and temperature distributions in the deformed billet, which are difficult to obtain by experiments. In order to better understand the various types of hot mills, it is desirable to first consider some of the basic principles involved in the rolling of all types of products. [31]

3.8. The Plastic Deformation of a Workpiece between Two Platens

Before examining the process of rolling, it is first pertinent to consider a cube of plastic material, such as steel at a hot-rolling temperature, compressed between two platens as illustrated in Figure 9. If the platens are such that there is no friction at the interface between the cubical workpiece and the platens, and the workpiece is small, then when a pressure in excess of the flow stress of the workpiece is reached, the workpiece will decrease in thickness and increase equally in the other two directions maintaining, to all intents and purposes, the same total volume.

If the cube is relatively large, however, the top and bottom surfaces of the workpiece will tend to flow more than the center, as illustrated in Figure 9.

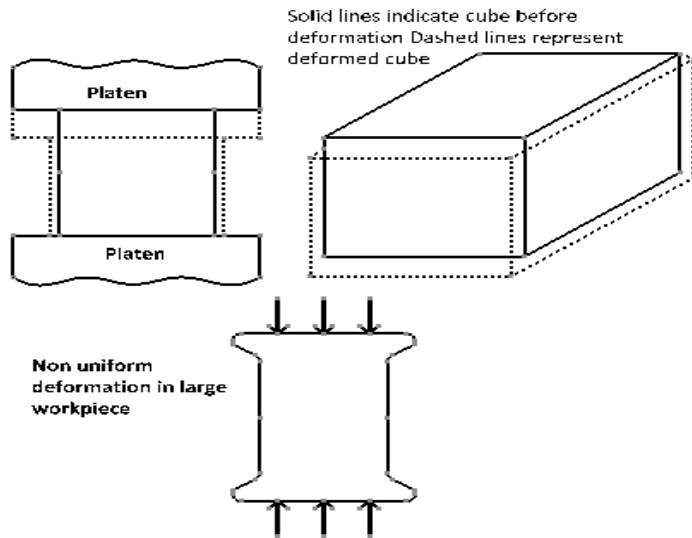


Figure 9. Sketches illustrating the deformation of a plastic workpiece

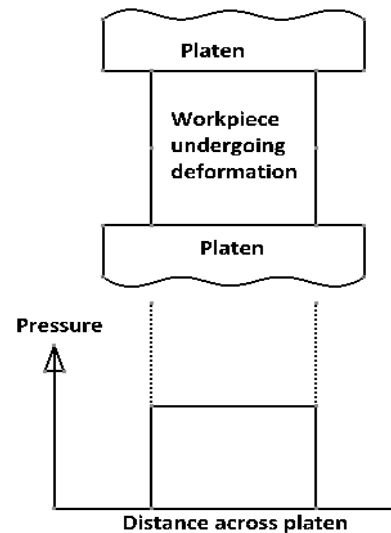


Figure 10. Pressure distribution across face of cube under frictionless condition

The pressure exerted by each frictionless platen throughout the area of contact is constant, as illustrated by Figure 10, this pressure being equal to the flow stress. The energy of deformation per unit volume may be shown to be

$$S \times \ln\left(\frac{1}{1-r}\right)$$

Where S is the flow stress and r is the reduction given to the workpiece in terms of the ratio of the change in its height to its original height.

In the case where friction exists between the platens and the workpiece, two important effects are to be observed. First, the pressure across the region of contact with each platen is not constant but increases towards the center of the contact area in an exponential manner, as indicated in Figure 11, this type of pressure distribution often being referred to as a friction hill. The greater the coefficient of friction, the higher is the hill. Thus the total deforming force, which corresponds to the volume under the pressure surface, increases with increasing friction. Second, the deformation of a small workpiece is no longer uniform throughout its thickness. Instead, the workpiece develops rounded edges as shown in Figure 12; the greater the friction, the more extensive the bowing or barrelling becomes. In addition, the energy of deformation per unit volume now exceeds $S \times \ln\left(\frac{1}{1-r}\right)$ to an extent depending on the geometry of the workpiece, the extent of its deformation and the magnitude of the coefficient of friction. In effect, therefore, friction appears to increase the flow stress of the piece.

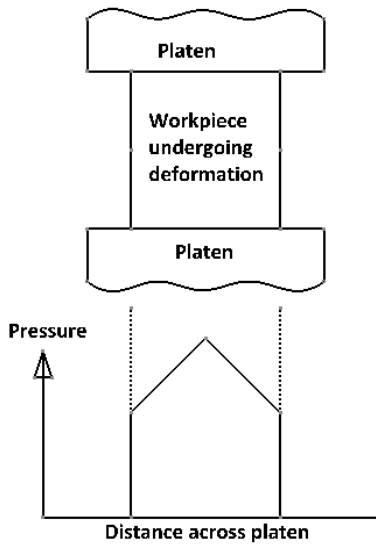


Figure 11. Pressure distribution across face of workpiece in the presence of friction

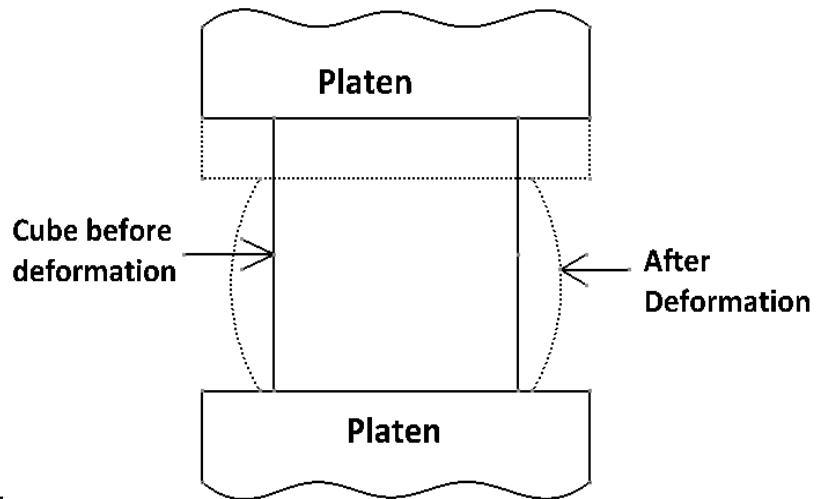


Figure 12. Barreling of a workpiece as a result of deformation under frictional conditions

It is now of interest to consider the case where the workpiece is restrained from flowing in one direction but can flow under friction less conditions at right angles, as illustrated in Figure 13. The pressure is again uniform across the area of contact but assumes a value close to 15.5 percent higher than the unrestrained flow stress of the piece. This value is known as the constrained compressive yield stress and the energy of deformation per unit volume therefore assumes the value of $1.1551.155S \times \ln\left(\frac{1}{1-r}\right)$.

When the expanding flow of the workpiece is restricted to one dimension, as discussed above, and friction occurs to impede this flow, the pressure distribution again assumes the form of a friction hill, as indicated in Figure 14, with the height of the hill being influenced by the magnitude of the coefficient of friction and the geometry of the workpiece.

3.9. The Effect of Tensile Stresses on the Deformation Process

If the workpiece, as it is being deformed by compressive stress under frictionless conditions, is subject to tensile stresses in the other two directions, as illustrated in Figure 15, the compressive stress required to deform the workpiece becomes less than its flow stress. If the tensile stresses are S_1 and S_2 where $S_1 > S_2$, then the compressive stress S_p required for deformation is, on the basis of the maximum shear theory of Tresca, given by $S_p = S - S_1$ where S is the normal flow stress. This pressure S_p is exerted uniformly across the area of contact as illustrated in Figure 15. However, the total energy of deformation per unit volume is unaffected

by the magnitude of the tensile stresses. If friction exists, then a friction hill again occurs. However, the bottom of each slope corresponds to the frictionless flow stress S_p so that the total deforming force is now determined not only by the coefficient of friction and the workpiece geometry but also by the tensile stress exerted on the workpiece. The total energy of deformation is, however, virtually unaffected by the tensile stress.

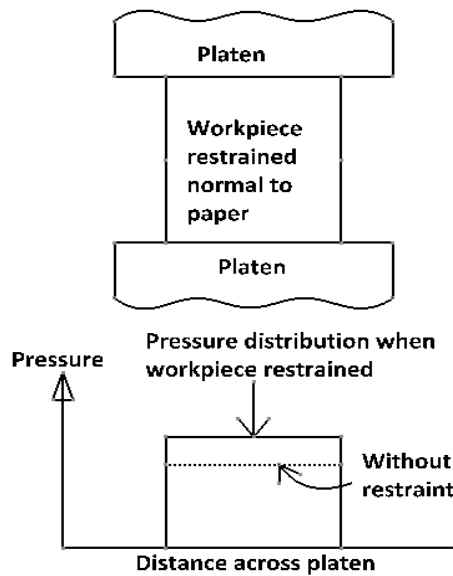


Figure 13. Pressure distribution when workpiece is restrained in one direction but in the absence of friction

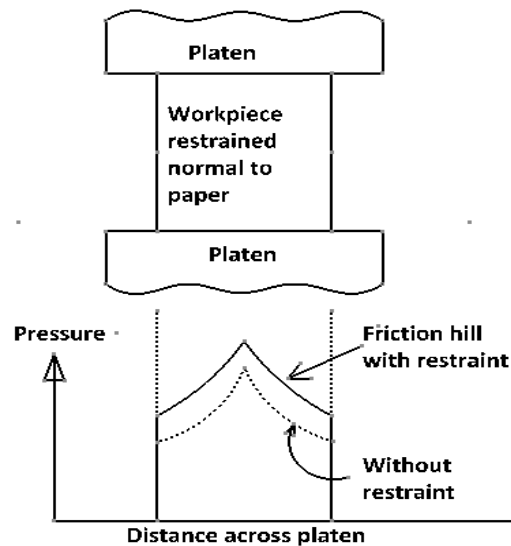


Figure 14. Pressure distribution with friction and restraint.

In the case where lateral flow of the workpiece is prevented, the minimum compressive stress at the bottom of each slope of the friction hill is now equal to $1.155S - S_1$.

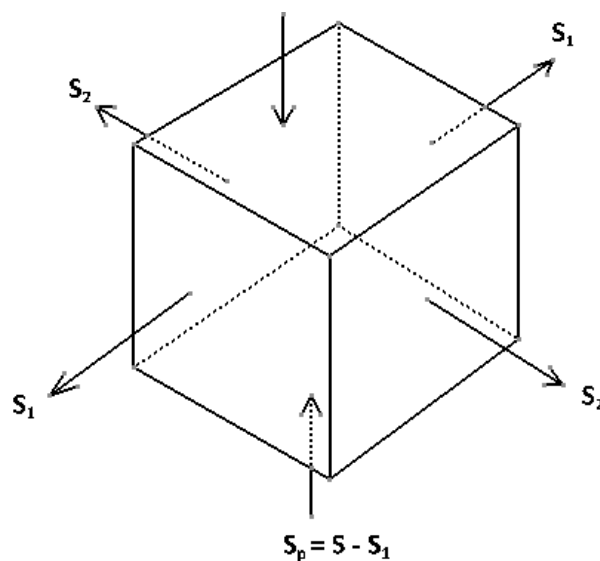


Figure 15. Sketch showing application of tensile stress to workplace

3.10. Energy Requirements in Non-flat Rolling

Curves for the approximate energy of deformation in the rolling of structural shapes in comparison with that required in flat rolling are shown in Figure 16. However, the energy required will depend on the cross sectional geometry of the workpiece and whether or not rolling lubrication is supplied.

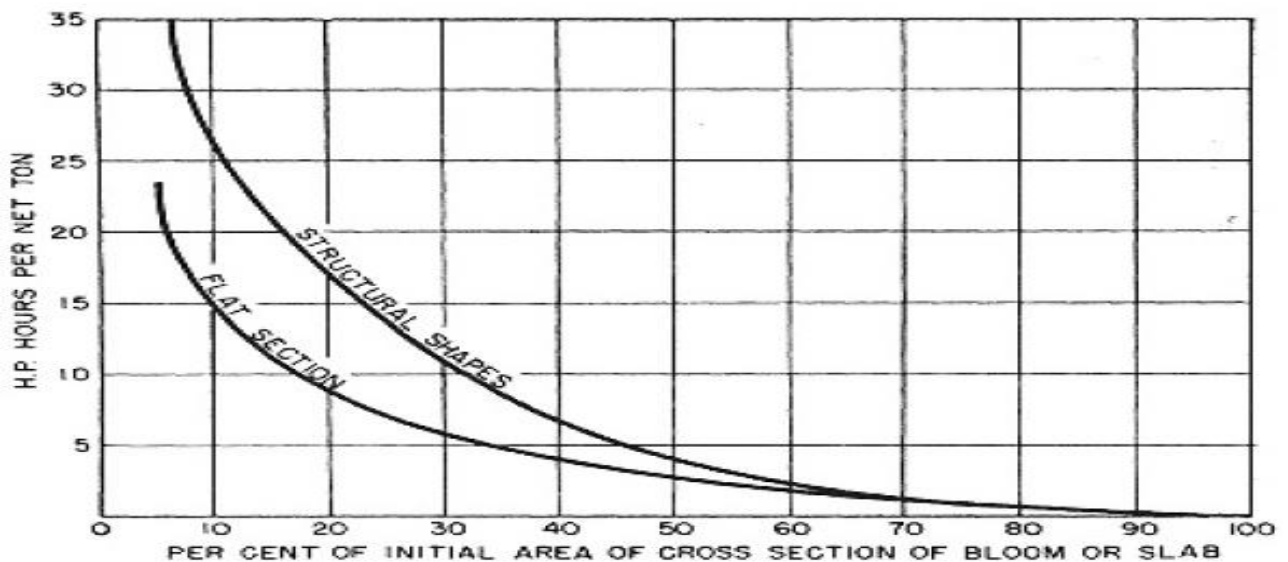


Figure 16. Horsepower –hours per net ton of steel rolled to percent reduction of cross-section for shapes and flat sections

The power N (in terms of Kw) for rolling of hot steel in groves is given by

$$N = \frac{fAk_m v_m + 2Pm v_{rm}}{102}$$

Where

f = correction factor (0.90 to 0.95 for hot rolling of steel),

A = reduction in cross-sectional area of the workpiece during the pass (mm^2),

k_m = mean resistance to deformation (kg/mm^2),

v_m = rolling speed (m/sec),

P = rolling force (kg),

m = coefficient of friction at the roll surface, and

v_{rm} = mean relative speed of the rolls and the workpiece in the areas of contact (m/sec).

It will be noted that the second term on the right hand side of the above equation represents the effects of friction in the roll bite.

In making computations, it is assumed a rectangular cross-sectional areas equivalent to the initial and final areas a_1 and a_2 respectively. The height or thickness of the entering bar h_1 is given by

$h_1 = \frac{a_1}{b_m}$ and the exit thickness h_2 by

$$h_2 = \frac{a_2}{b_m}$$

Where

b_m is the mean of the entry and exit widths b_1 and b_2 , or

$$b_m = \frac{b_1 + b_2}{2}$$

This method of replacing cross-sectional areas with rectangles is illustrated by Figure 17.

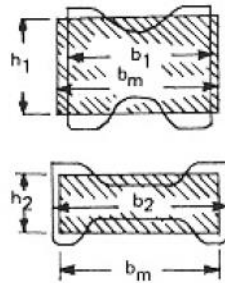


Figure 17. Method of Replacing

The effective length of the arc of contact l_d in the roll bite is determined from

$$l_d = \left[\frac{(D_a - h_2)(h_1 - h_2)}{2} \right]^{\frac{1}{2}}$$

Where

D_a is the distance between the roll axes.

The rolling force P may then be calculated from

$$P = k_m b_m l_d$$

The workpiece leaves the roll bite at a mean rolling speed v_m

Where

$$v_m = \frac{r_m n \pi}{30}$$

Where

r_m = mean roll radius with the peripheral speed v_m at which the workpiece leaves the pass and

n = the rotational speed of the rolls (rpm).

The mean roll radius r_m may be calculated as follows. Referring to Figure 18,

$$h_t = \frac{A_t}{b}$$

And

$$h_b = \frac{A_b}{b}$$

Where

A_t and A_b are two areas of arbitrary sizes, the sides of which are formed by the working peripheries of the pass (a-b and c-d) as well as by one straight line parallel to, and two straight lines perpendicular to, the roll axes. Hence h_t and h_b determine the position of the mean or effective roll surfaces (A-A and B-B) and the mean radii of the two rolls r_{mt} and r_{mb} . The neutral line N-N of the roll bite must lie half way between A-A and B-B so that

$$r_{mt} = r_{mb} = r_m$$

The mean relative speed v_{rm} may be approximated by

Where

r_i = the roll radius at any arbitrary point i on the roll periphery, and

x = the number of points considered.

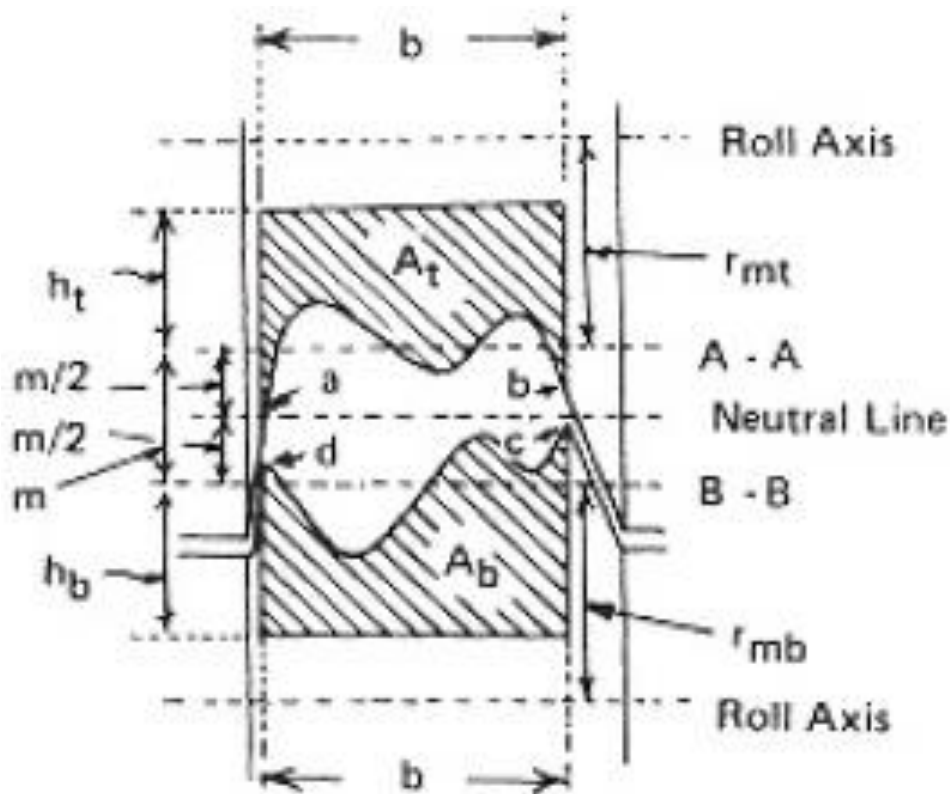


Figure 18. Sketch illustrating the determination of the neutral line of a pass

3.11. Frictional Effects in Hot Rolling

To transmit deformation energy from the work rolls to the workpiece in a hot rolling operation, friction at their interfaces in the roll bite is necessary.

Excessive friction, however, tends to restrain the deformation and results in undesirably high rolling forces and spindle torques. Too little friction, on the other hand, results in either roll slippage or the failure of the workpiece to enter the roll bite.

In the development of a detailed understanding of the hot-rolling process, a knowledge of the effective coefficient of friction at the roll-workpiece interfaces therefore becomes essential.

In recent years, hot-rolling lubricants, such as blended oils, have found extensive use on hot-strip mills. These have provided many benefits, not only reducing rolling force and torque requirements, but increasing mill productivity (by lessening the number of work-roll changes), increasing work roll life in terms of the weight of steel rolled, improving the surface quality of the strip and decreasing pickling costs. However, rolling lubricants must be applied carefully with the realization that other changes in the rolling operation may be necessary. For example, reduced rolling forces will result in smaller crowns in the strip profile unless appropriate changes are made in the work-roll crowns or suitable roll bending is applied. Strip with flatter profiles is more likely to exhibit finger ridging after cold reduction. Moreover, the application of a lubricant should be initiated after the head end of the workpiece has entered the roll bite and terminated before the tail end leaves the bite. Failure to follow these precautions might result in gagging or the failure of the workpiece to enter the roll bite. Furthermore, excessive oil contamination of the recycled mill cooling water will provide continual roll-bite lubrication and result in the same consequences. [21]

CHAPTER FOUR

FINITE ELEMENT MODELING and OPTIMIZED ANALYSIS of UIC 60 RAIL ROLL PASS

4.1. Optimization of Roll Pass Process

The ultimate goal of roll-pass design is to acquire the desired geometry and tolerances with the least cost while preventing from defects on the work piece. This can be categorized into two factors: (a) factors related to cost and (b) factors related to the quality of the product. For example, it is desired to maximize the area reduction percentage in order to reduce the number of passes (cost factor), but it is not desired if the severe deformation causes defects such as overfills on the work piece (quality factor). Also, it is desirable to have more uniform and gradual cross sectional area reduction (quality factor). However, it is also desirable to use the maximum capacity of the rolls (cost factor). These goals are sometimes conflicting with each other and optimizing one factor does not necessarily mean that the other factors are improved or not. There are also constraints; some are very specific (e.g., maximum roll load allowed) while some are delicate (e.g., non-uniform strain distribution which may cause micro structural problems). Many factors are given and thereby uncontrollable in order to improve the existing roll-pass design. For example, the initial and final geometry of the work piece, the rolled-material are some of them.

The controllable factors include the geometry of the intermediate passes, the roll diameter, and rolling speed. In this study, the geometry of the intermediate passes is chosen which is considered to be the most effective in roll-pass design. Since it is not easy to see the direct effect of the different geometry of the intermediate passes on quality of the product, four measurable quantities, which are called evaluation criteria, from the numerical simulation are chosen which are related to the goals. They are:

- Reduction in number of passes
- Maximum use of capacity (roll force balance)
- Uniformity in strain distribution
- Groove fill percentage at the final pass

The reduction in number of passes is clearly related to the production costs. If an extra-pass is inadvertently designed with very small cross sectional area reduction, it is directly related to

an extra cost and time. Roll force balance is important in the sense that it uses the maximum capacity of the rolls. In many cases, the same capacity of rolls is used for several passes because of the ease of roll interchangeability. If the roll separating force of a certain pass is very small cross-sectional area reduction, this also represents extra cost.

Uniform strain distribution is desirable because it is related to the microstructure and also related to reducing the possibility of defects of the product. Before rolling, it is possible that there are defects from ingot. A highly-concentrated strain may cause the surface cracks on that area. Finally, groove fill percentage is related to the dimensional tolerances. It is believed that the better tolerance at the end of roughing passes leads to better tolerances at the end of finishing passes.

Like the goal factors, these evaluation criteria are sometimes competing with each other and sometimes are not. For example, if the number of passes goes over the limit, it will break the roll or the desired geometry (groove fill percentage) will be achieved. In other case, reducing the number of passes can lead to more balanced roll forces and better groove fill percentage.

Optimization of rolling, providing that process is void of catastrophic interruptions (such as appearance of significant surface cracks, complete fractures or misguided work piece), can be evaluated on the basis of the following indicators:

- i. **Yield:** The yield (output) of the rolling process can be classified as the percentage (%) of first class product, % second class and % of scrap.
- ii. **Productivity:** The above output is achieved at the productivity rate of x products per hour.
- iii. **Costs:** In order to realize a rolling process, the certain amount of man-hours, volume of feed, quantity of cooling and lubricating media, quantity of the fuel and electrical energy, and certain quantity of tools, are required, which all present the production costs.
- iv. **Reliability:** This is the probability that the above defined process will continue successful running until the time is reached.

Nowadays, there are basically two approaches to the mathematical modeling of shape rolling. The first, traditional, empirical approach in which relatively simple mathematical formulas have been derived in order to predict the global process parameters such as free spread, roll separating force and roll torque. Typically, the formulas contain sets of coefficients that

approximate the effect of various rolling conditions. The approach can provide mean values of stress, strain and strain rate, experienced by the material in a rolling pass.

The second, up-to-date approach is based on numerical methods, mainly the finite-element method. Using the FEM, not only the global forces and displacements are successfully predicted, but also the local distribution of strains, strain rates, stresses and temperatures in the deformation zone of a work piece can be followed. Obviously, the numerical approach is superior to the empirical one, but sometimes, its practical application may be hindered by its complexity and required computational power. Due to the development of the computer science and numerical modeling techniques, FEM has been become popular and efficient in solving metal forming problems. [30]

4.2. General Manufacturing Process of Rail

The rail sections are generally made of carbon steels by hot rolling process. The rolling of rail section is carried out in number of passes. For converting initial steel bloom into final rail section, the bloom is passed between numbers of rollers. Each roller has different grooves on it. The shape of groove decides the rolled section at each pass.

The production process of a rail consists of three steps:

- Hot rolling,
- Cooling and
- Straightening.

After rolling, the temperatures in the rail are higher than 900⁰C, because of which the rail is placed on beds until it acquires a temperature close to room (ambient) temperature. In this process, the longitudinal shape of the rail changes due to the different cooling speeds of its different parts. Next, the rail is fed into the straightening machine, where it is subjected to a set of bending cycles in order to remove these displacements and curvatures.

4.3. Standard Rail Sections and their Specifications

Rails are the members of the track laid in parallel lines to provide an unchanging, continuous, and level surface for the movement of trains.

Rails are mainly of three types so far used. These are double headed rail, bull headed rail and flat-footed rail. The first rails used were double headed and made of an I or dumb-bell section.

The idea was that once the head wore out during service, the rail could be inverted and used. Experience, however, showed that while in service the bottom table of the rail was dented to such an extent because of long and continuous contact with the chairs that it was not possible to reuse it. The problem faced with double headed rail led to the development of the bull headed rail, which had an almost similar shape but with more metal in the head to better withstand wear and tear. This rail section had the major drawback that chairs were required for fixing to the sleepers. A flat-footed rail is an inverted T-type section.

The rail is designated by its weight per unit length. In FPS units, it is the weight in lbs per yard and in metric units it is in kg per metre. A 52 kg/m rail denotes it has a weight of 52 kg/metre. The standard rail sections in use in railways are 60 kg, 52kg, 90 R, 75 R, 60 R and 50 R. The two heavier rail sections, 60kg and 52kg, were recently introduced and are designated in metric units. Other rails are designated as per the revised British Standard specifications and are designated in FPS units though their dimensions and weight are in metric units. Mainly 60kg and 52kg are widely used in railway. [33]. According to the information that I get from Ethiopia Railway Corporation, the type of rail section that deployed in our country is U74 type which is correspond to 50Kg. rail section.

Table 6. Detail of standard rail sections

Rail section	Wt/m(kg)	Dimensions(mm)					
		A	B	C	D	E	F
52 kg	51.89	156	136	67	15.5	51	29
60 kg	60.34	172	150	74.3	16.5	51	31.5

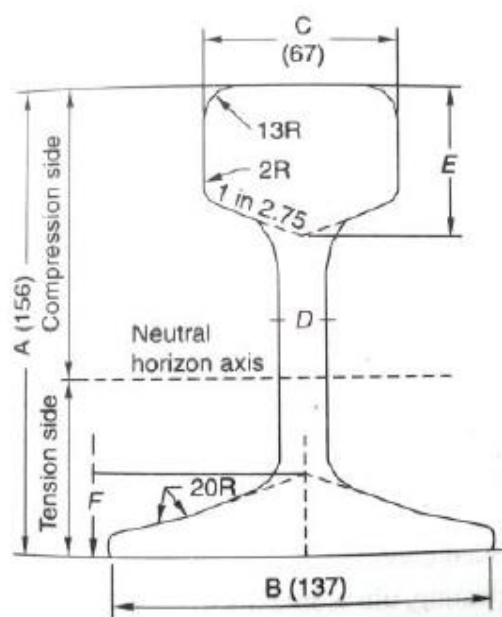


Figure 19: 60Kg and 52Kg rail sections designations

4.4. Selection of the Rail Type

From the standard rail sections, the most widely used and recently introduced one is UIC 60 (60kg/m) rail type. Therefore, for this study, I select this standard rail. The two-dimensional finite element model that describes its section is shown in figure 20.

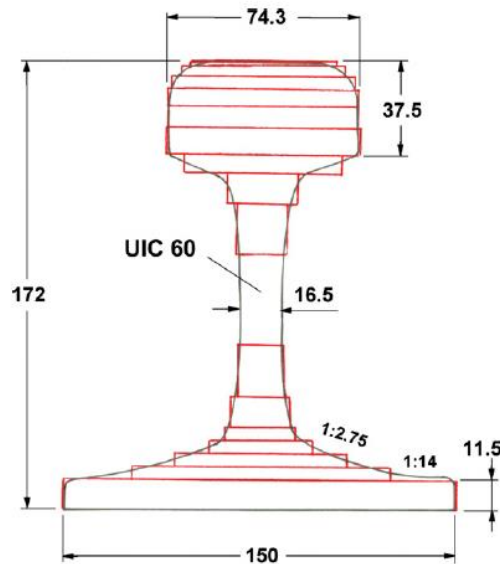


Figure 20: Two-dimensional Finite element models of UIC 60 rail

4.5. Material Selection for rail and roller

The selection of a material for a machine part or structural member is one of the most important decisions the designer is called on to make. So in the following section, the material of rolling stock and roller is selected based on their mechanical and thermal properties.

4.5.1. Material selection for rail

The standard rail section is generally made from steel blooms by hot rolling process. To be able to withstand stresses, they are made of carbon steel. Therefore, to withstand thermal and mechanical stress, and to improve the weld ability of the rail, the structural steel of grade 880 with chemical composition and mechanical properties as shown in table 7 and 8 are selected.

Table 7 Chemical Composition of grade 880 steel

Grade	C	Mn	Si	S (max.)	P (max.)	Al (max.)
880	0.6-0.8	0.8-1.3	1.3-0.5	0.035	0.035	0.02

4.5.2. Material selection for Rollers

Since in the rolling operation, the deformation of the workpiece is accomplished by the rolls, these components of a mill must, of necessity, be harder and more resistive to deformation than the workpiece. A roll must have adequate mechanical strength and wear resistance and, at the same time, provide appropriate grip and fire crack resistance. For this application, low hardness steel rolls (normally cast steel containing 0.4 to 1.0 percent carbon) with a hardness of 40 Shore C are used, the higher carbon grades giving a better wear resistance and exhibiting less of a tendency to metal pickup since they contain less ferrite. Titanium and its alloys are similar in strength to moderate-strength steel but weigh half as much as steel. The material exhibits very good resistance to corrosion, has low thermal conductivity, is nonmagnetic, and has high-temperature strength. Its modulus of elasticity is between those of steel and aluminum at 16.5 Mpsi (114 GPa). The disadvantages of titanium are its high cost compared to steel and aluminum and the difficulty of machining it. [28] By evaluating all these, the selected rollers material that satisfy the above criteria is Titanium alloy, with mechanical properties shown in table 8.

Table 8. Material Properties of Rolling Stock and Rollers Used for Simulation

Properties	Rolling Stock (Bloom) Material	Rolling and Stands Material
Material	Structural Steel	Titanium Alloy
Density (kg/m ³)	7850	4620
Specific Heat (J/Kg.C)	434	522
Isotropic Elasticity		
Young`s Modulus (GPa)	200	96
Poisson`s ratio	0.3	0.36
Bulk Modulus (GPa)	166.67	114.29
Shear Modulus (GPa)	76.923	35.294
Bilinear Isotropic Hardening		
Yield Strength (GPa)	0.25	0.93
Tangent Modulus (GPa)	1.45	2.15

4.6. The Initial Parameters Used for Designing

▪ Selection of Initial Bloom Temperature

Saral Dutta. B. Tech. [35] in his book entitled “HOT ROLLING PRACTICE” describes that to make them soft and thus suitable for rolling, the bloom should be initially heat from 1100⁰C to 1300⁰C. Different literature also describes an initial rolling temperature which are in this ranges. So for the analysis of rail rolling, I use an initial bloom temperature of 1200 °C.

▪ Selection of Initial Roller Speed

By visualizing the speed of the roller of different large sections rolling manufacturing factories in Ethiopia and by reviewing different literatures, the speed of the first roller is set to 100 rpm. Whereas the speed of the remaining rollers are calculated according to the 2nd law of rolling which is described in section 3.6.

▪ Selection of Initial Bloom Cross section

We can found different standard size of bloom in market. But to roll a standard UIC 60 rail of length 12.5m in ten passes, It needs a square cross section bloom with area 108,900mm².

▪ Selection of Initial Roller surface Temperature

Before the rolling operation is begin, the rollers will have a room temperature which is In the range between 16 and 26 °C (61 and 79 °F), with an average of 20 °C (68 °F). So I select the roll surface temperature as 20°C.

▪ Friction between roller and workpiece

The friction between the workpiece and the roller is depend on the initial temperature of the workpiece. The formula to approximate their relation is described by Robert William [21] which is:

$$m = 2.7 \times 10^{-4}T - 0.08$$

Where m is the coefficient of friction and T is the workpiece temperature of the wrokpiece.

But we already set the workpiece temperature as 1200⁰C, therefore, the coefficient of friction, m becomes

$$m = 2.7 \times 10^{-4} \times 1200 - 0.08 = 0.244$$

4.7. Selection of an Optimized Roll Pass

Roll passes must be carefully designed and the rolling operation should be properly supervised in order to meet the stringent dimensional and quality specifications. The case study chosen to demonstrate the integrated approach is to roll a 340x340mm square bloom to a UIC 60 rail which is standard and widely applicable.

In rolling, the conversion of initial bloom to final section is achieved in number of passes. The number of passes generally depends on final section. The initial bloom taken is having square cross section of 340 mm x 340 mm and the final rail section is as already selected in section 4.4 of page 57 which is UIC 60 rail. For maintaining smooth flow, the reduction in cross-sectional area is taken according to geometrical progression series. The exit sections at each roller pass are designed based on the combination of rolling sequences for an entry bar rolled in a groove to an exit shape which are listed in table 3 of section 3.2. As much as possible, during selecting of the sequence, those who named “commonly” applicable sequence are selected. And finally the following roughing and finishing passes sequence are selected.

4.7.1. Roughing Pass

Square Bloom → Box → Oval → Square → Oval → box Pass

Calculating Parameters for the 1st Pass (Box pass)

The initial square cross sectional area of the workpiece before entering the box pass is 115,600 mm².

As discussed in before, the recommended area of reduction from square to box pass is 25% Therefore,

$$\text{Area of reduction} = 25\% \times 115,600 = 28,900 \text{ mm}^2$$

Therefore, the area of the section after passing the box pass becomes

$$115,600 - 28,900 = \underline{86,700 \text{ mm}^2}$$

From the formula in the above table, we can calculate the following parameters for box pass

$$B_p = 329.2 \text{ mm} \quad H_1 = 263.36 \text{ mm} \quad r = 33 \text{ mm} \quad r_1 = 27 \text{ mm} \quad D = 725 \text{ mm} \quad S = 7.25 \text{ mm}$$

The angular speed of the roller for pass 1 is taken as $n = 100 \text{ rpm}$

By inputting the value of the parameters for box pass calculated above in DEFORM 3D software, the profile shown in figure 21 is found after the bloom leaving the box pass.

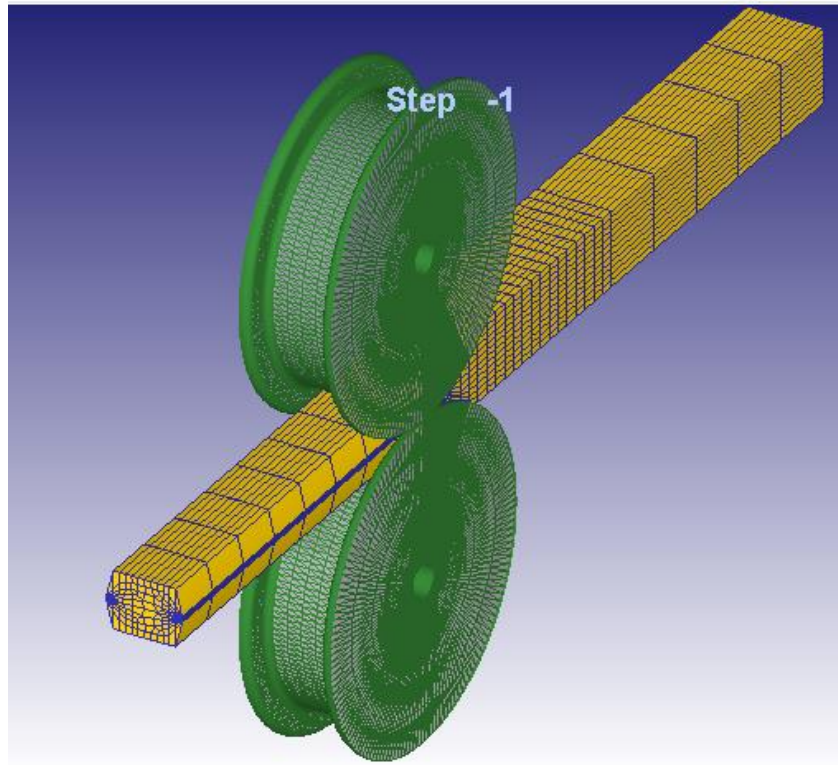


Figure 21. The shape of the workpiece after the exit of the 1st pass

Calculating Parameters for the 2nd Pass (Oval pass)

The initial box cross sectional area of the workpiece before entering the oval pass is 86,700 mm².

The maximum recommended area of reduction from box to oval pass is 25%

Therefore,

$$\text{Area of reduction} = 25\% \times 86,700 = 21,675\text{mm}^2$$

Therefore, the area of the section after passing the oval pass becomes

$$86,700 - 21,675 = \underline{65,025\text{mm}^2}$$

From the formula in the above table, we can calculate the following parameters for oval pass

$$B_p = 352.4\text{mm}, B_b = 330\text{mm} \quad H_1 = 234.94\text{mm} \quad R = 190.89\text{mm} \quad r_1 = 25\text{mm}$$

$$D = 725\text{mm}, \quad S = 6\text{mm}$$

From the 2nd law of rolling pass design mentioned above, we can calculate the angular speed after exiting the oval pass as $n = 133\text{rpm}$

By inputting the value of the parameters for oval pass calculated above in DEFORM 3D software, the profile shown in figure 22 will be found after the bloom leaving the oval pass.

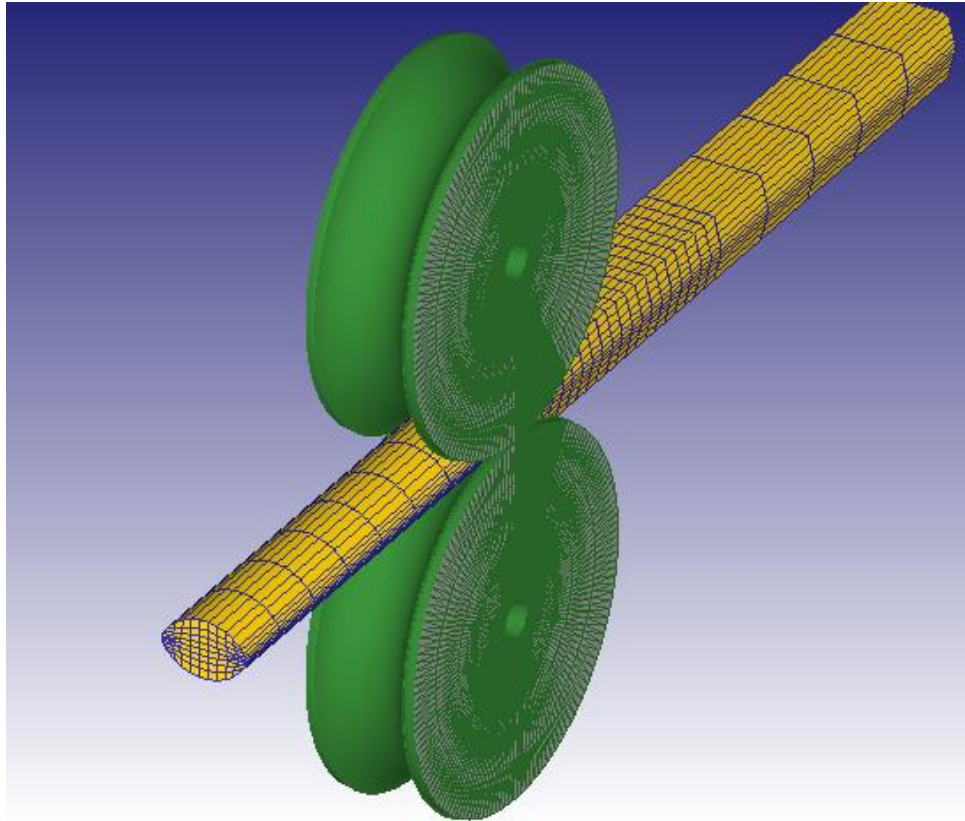


Figure 22. The shape of the workpiece after the exit of the 2nd pass

Calculating Parameters for the 3rd Pass (Square pass)

The initial oval cross sectional area of the workpiece before entering the square pass is 65,025mm².

The maximum recommended area of reduction from oval to square pass is 35%

Therefore,

$$\text{Area of reduction} = 35\% \times 65,025 = 22,758.75\text{mm}^2$$

Therefore, the area of the section after passing the oval pass becomes

$$65,025 - 22,758.75 = \underline{42,266.25\text{mm}^2}$$

From the formula in the above table, we can calculate the following parameters for square pass

$$B_p = H_1 = 290.745\text{mm} \quad B_b = 0\text{mm} \quad r = 21\text{mm} \quad r_1 = 29\text{mm}, \quad D = 725\text{mm}, \quad S = 5\text{mm}$$

From the 2nd law of rolling pass design mentioned above, we can calculate the angular speed after exiting the square pass as $n = 204\text{rpm}$

By inputting the value of the parameters for square pass calculated above in DEFORM 3D software, the profile shown in figure 23 will found after the bloom leaving the square pass.

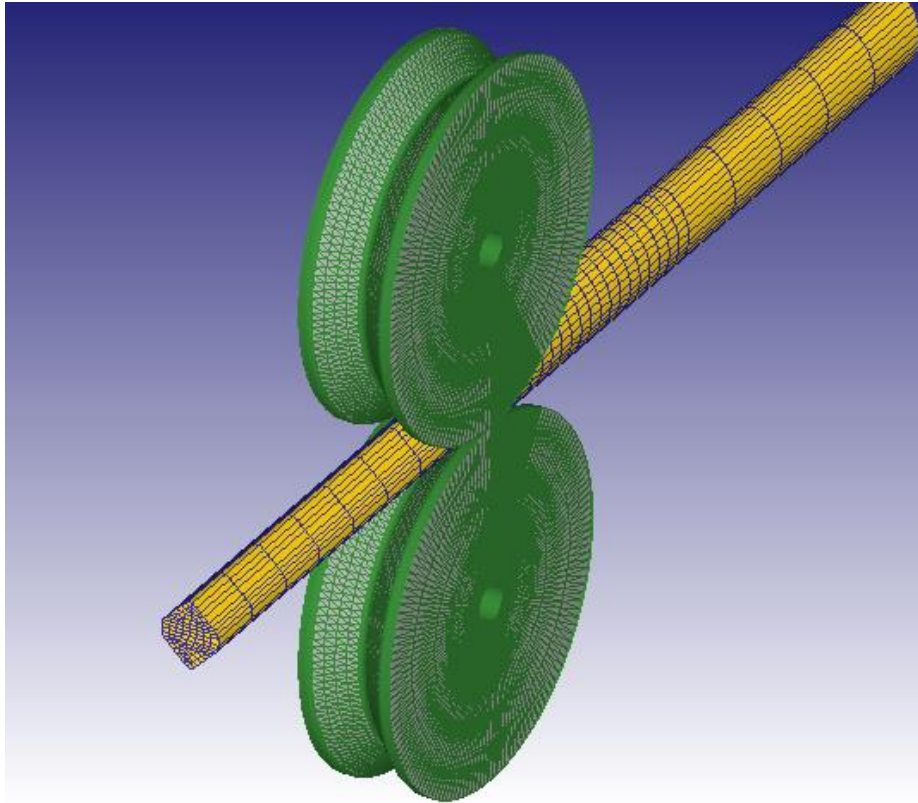


Figure 23. The shape of the workpiece after the exit of the 3rd pass

Calculating Parameters for the 4th Pass (Oval pass)

The initial square cross sectional area of the workpiece before entering the oval pass is 42,266.25 mm².

The maximum recommended area of reduction from square to oval pass is 25%

Therefore,

$$\text{Area of reduction} = 25\% \times 42,266.25 = 10,566.5625\text{mm}^2$$

Therefore, the area of the section after passing the oval pass becomes

$$42,266.25 - 10,566.5625 = \underline{31,699.6875\text{mm}^2}$$

From the formula in the above table, we can calculate the following parameters for oval pass

$$B_p = 246.05\text{mm}, B_b = 231\text{mm} \quad H_1 = 164.04\text{mm} \quad R = 133\text{mm}$$

$$r_1 = 17\text{mm} \quad D = 725\text{mm}, \quad S = 4\text{mm}$$

From the 2nd law of rolling pass design mentioned above, we can calculate the angular speed after exiting the oval pass as $n = 272\text{rpm}$

By inputting the value of the parameters for oval pass calculated above in DEFORM 3D software, the profile shown in figure 24 will be found after the bloom leaving the oval pass.

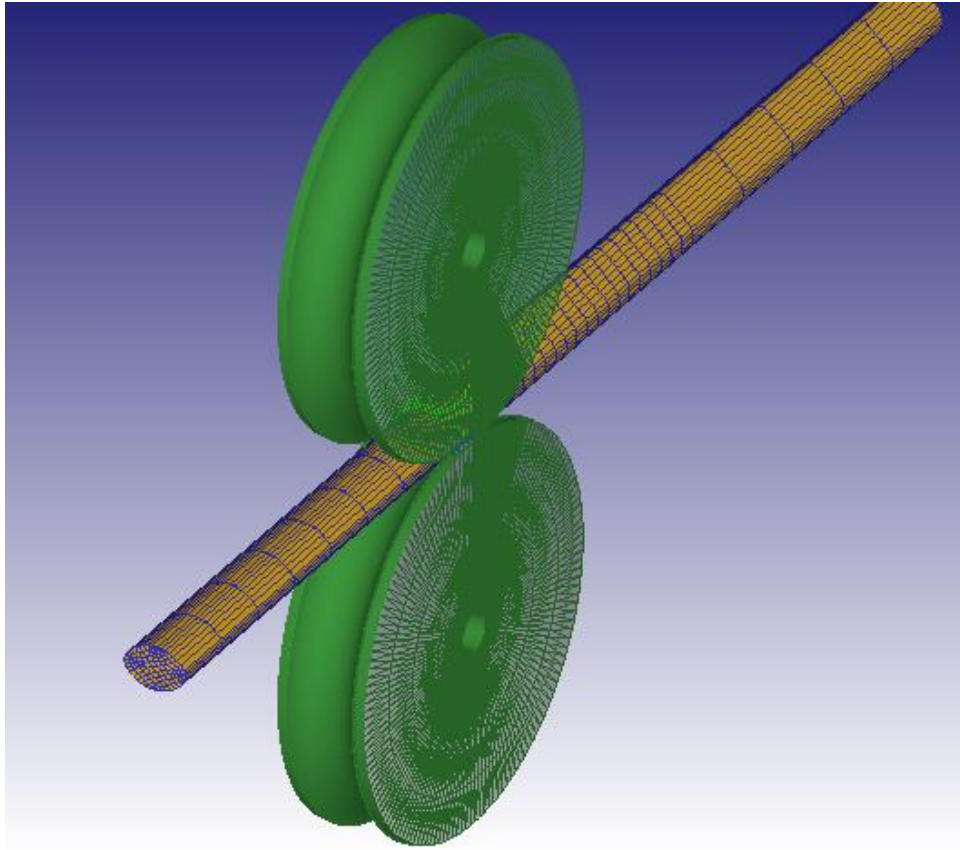


Figure 24. The shape of the workpiece after the exit of the 4th pass

Calculating Parameters for the 1st Pass (Box pass)

The initial oval cross sectional area of the workpiece before entering the box pass is $31,699.6875\text{mm}^2$.

The desired dimension of the workpiece after leaving the 5th pass should be $172 \times 150\text{mm}$ which is the height and width of the final UIC Rail respectively. Therefore, the area after 5th pass becomes $25,800\text{mm}^2$

The area of reduction becomes $31,699.6875 - 25800 = \underline{5,899.6875\text{mm}^2}$

Therefore, the ration of reduction of area at the 5th pass is $5,899.6875/31699.6875 = 18.6\%$ and which is below the maximum possible reduction are from oval to box pass which is 20%.

Therefore,

$$B_p = 172\text{mm} \quad H_1 = 150\text{mm} \quad r = 15\text{mm} \quad r_1 = 14\text{m} \quad D = 725\text{m} \quad S = 2.5\text{mm}$$

From the 2nd law of rolling pass design mentioned above, we can calculate the angular speed after exiting the box pass as $n = 334\text{rpm}$

By inputting the value of the parameters for box pass calculated above in DEFORM 3D software, the profile shown in figure 25 is found after the bloom leaving the box pass.

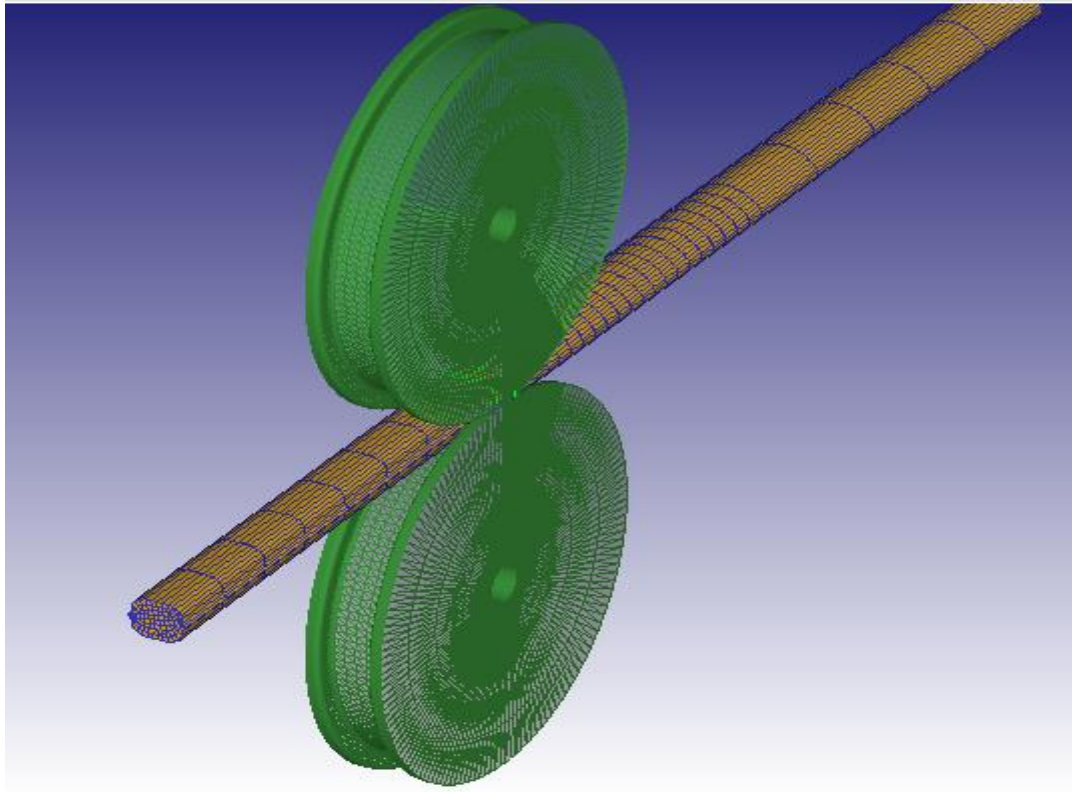
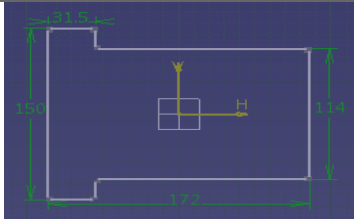
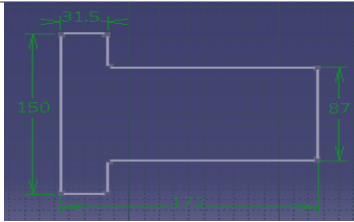
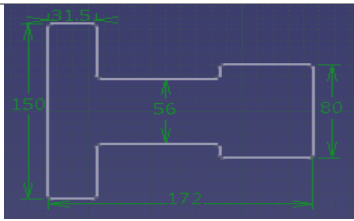
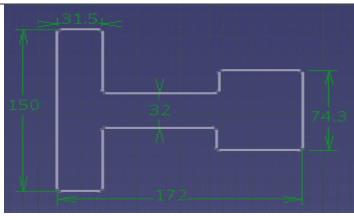
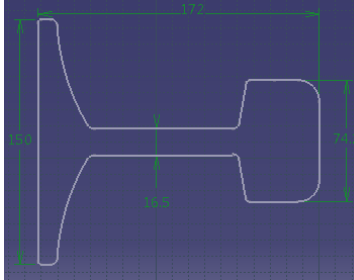


Figure 25. The shape of the workpiece after the exit of the 5th pass

4.7.2. Finishing Pass Design for UIC 60 Rail

To obtain the profile of UIC 60 rail shown above from a 172x150 cross section bloom which is found at the fifth pass shown in figure 25, the following 5 passes are designed. As we can see from table 9, the percentage reduction in area is decreasing as approaching to the last pass. The reason is to obtain a good surface finish at the last pass and to maintain a smooth flow. The designed exit sections at each roller pass with their corresponding angular speed calculated based on the law of rolling pass design are shown in table 9.

Table 9: The Design of Finishing Passes (Pass 6-10)

Pass No.	Profile	Area of Cross-section (mm ²)	Reduction in Area (%)	Speed (RPM)
6		20,742	19.6	415
7		16,948.5	18.3	508
8		14,045	17.1	613
9		11,695.55	16.7	736
10		9,991.05	14.6	862

4.8. Simulation of the Roll Passes

All the 10 passes shown above then simulated Using DEFORM 3D Software to determine the induced stresses during the rolling of the material, the temperature distribution during rolling, the strain, the strain rate, the damage during rolling, the pressure during rolling etc. The designed set up of rolls and stands for the rolling stands is shown in figure 26.

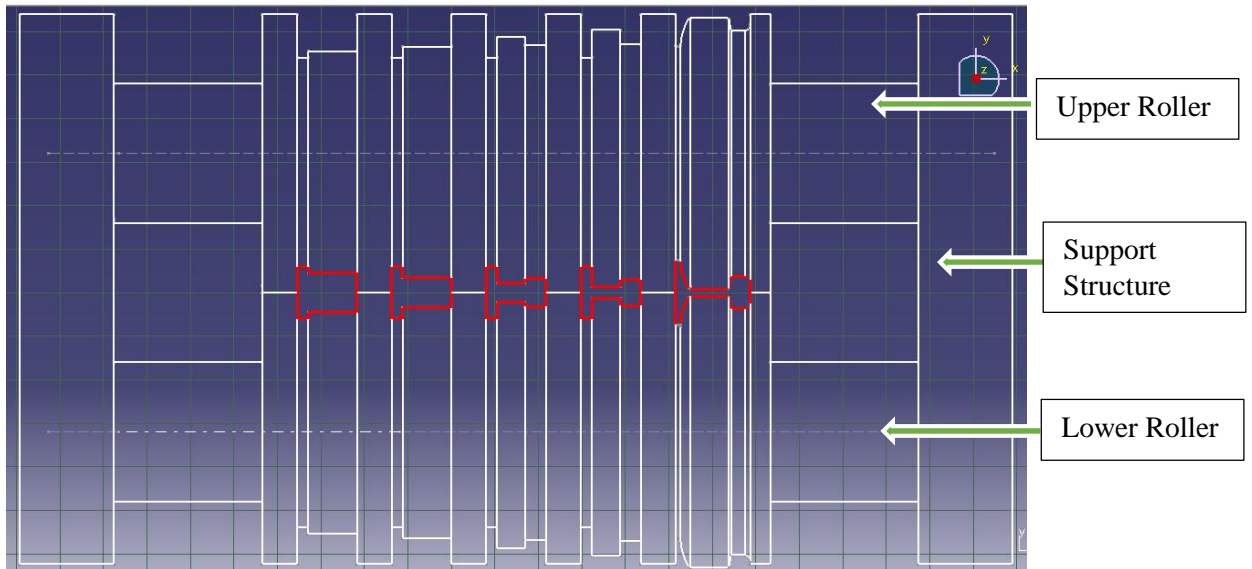


Figure 26. Designed set up of rolls and stands

After all the design data calculated above are inserted in the DEFORM 3D software, the arrangement of the different grooved rollers which are needed to deform a UIC 60 rail is look like the one shown in figure 27.

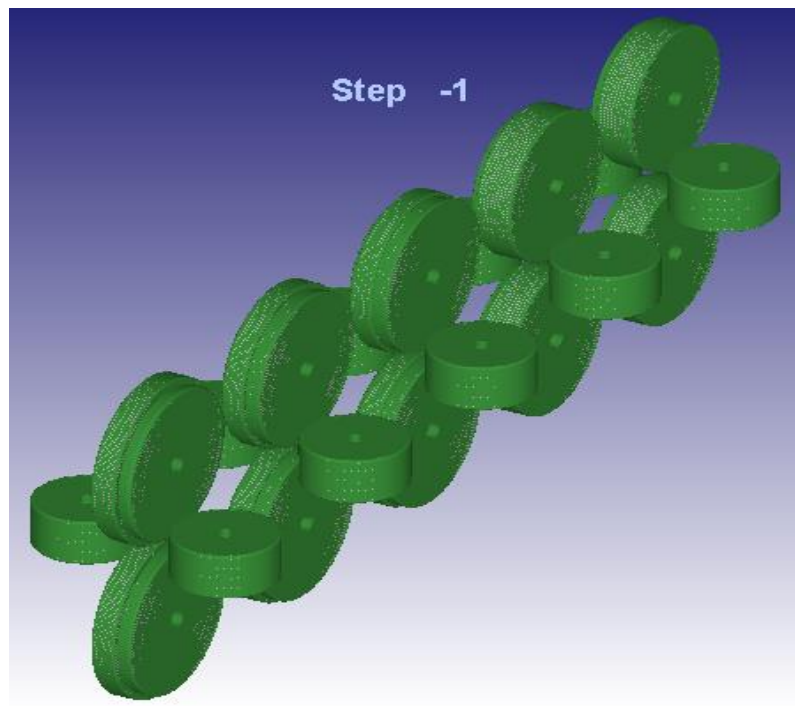


Figure 27. The arrangement of the designed rollers in DEFORM 3D Software

Finally after finishing inputting design data in the pre processor and running the model in simulator, the results which are displayed in the next chapter can be found in the post processor of the DEFORM 3D.

CHAPTER FIVE

RESULTS and DISCUSSIONS

Rail hot rolling is a multi-pass process where the initial rectangular cross-section geometry of a bloom is transformed into the desired rail shape by means of a sequential forming performed by successive passes between pairs of shaped rolls (grooves).

As we have seen from the previous chapter, the roll passes for the rolling of a UIC 60 rail from a bloom of dimension 340X340mm is designed. To obtain the desired shape, the rectangular bloom rolled 10 passes, 5 roughing pass and 5 finishing passes using 36 rollers.

To examine the thermos-mechanical effect of the rolling operation the designed passes are simulated using finite element analysis (DEFORM 3D)

As discussed in the previous section finite element metal forming software helps for predicting the effect before actual implementation. By doing so, it is possible to avoid the use of actual trial and errors as in earlier times, even if the FEM metal forming software itself is designed based on empirical relations.

Deform 3D software has three operational components. These are preprocessing, simulation results and post processing.

The main aim of this analysis is to design a roll pass that helps to manufacture a UIC 60 rail with free of defect and improving the life of the tools. In order to achieve these, the effect following important parameters should be predicted.

5.1. Interpreting state variables

a. Damage

Damage specifies the damage factor at each element. The damage factor can be used to predict fracture. The damage factor increases as a material is deformed. Fracture occurs when the damage factor has reached its critical value. The critical value of the damage factor must be determined through physical experimentation. Damage factor, D_f , is defined by

$$D_f = \int \left(\frac{\sigma^*}{\sigma} \right) d\varepsilon$$

Where σ^* is the tensile maximum principal stress, σ is the effective stress, and $d\varepsilon$ is the effective strain increment.

Damage generally relates to the likelihood of fracture in a part. The specific definition of damage is dependent on the method of calculation selected in the pre-processor. Damage is not a good indicator of fracture in tooling. Stress components should be used for die failure analysis.

The damage value at which fracture initiates varies substantially from material to material, and can even vary for a given material with different annealing treatments. However, for a given material with a given annealing treatment, critical damage value at fracture is reasonably repeatable. Damage value can be used in two ways:

- Evaluating alternatives: In problem solving a job that is known to fracture, or in analyzing a job where ductile fracture is known to be a risk. Several alternatives can be analyzed in DEFORM. The alternative with the lowest damage value is the best alternative for minimizing the likelihood of fracture.
- Comparing a design to a known critical value. Critical damage values can be estimated from prior experience with a given material on a part that is known to fracture. Running a DEFORM simulation of a process known to cause stretch cracking in the part will give an upper bound value for damage. Running a simulation on a part made of the same material that is known *not* to crack will give a good lower bound value. The ideal part is a marginal process, that is: one that cracks occasionally, but not on every part. If the peak damage value from the DEFORM analysis corresponds with the fracture site on the part, this will give a good estimate of the critical value. Designs with a damage value 10% to 20% or more below this value should be safe from fracture, if material and anneal conditions are the same.

Fracture within DEFORM-3D is available. To implement this, only a few settings are required. The first setting that is required is the critical damage value for fracture. This is specified within the material properties window -> Advanced tab (See Figure 28). Within this window the damage criteria can be specified. By clicking the data window icon next to the criteria, a critical value can be input to the system (See Figure 29). The critical value to use is very dependent on the material being used, the processing methods to produce the material, deformation history, etc....but for steel it cannot be greater than 10. So for this design purpose, I use a damage value of 8 as shown in figure 29

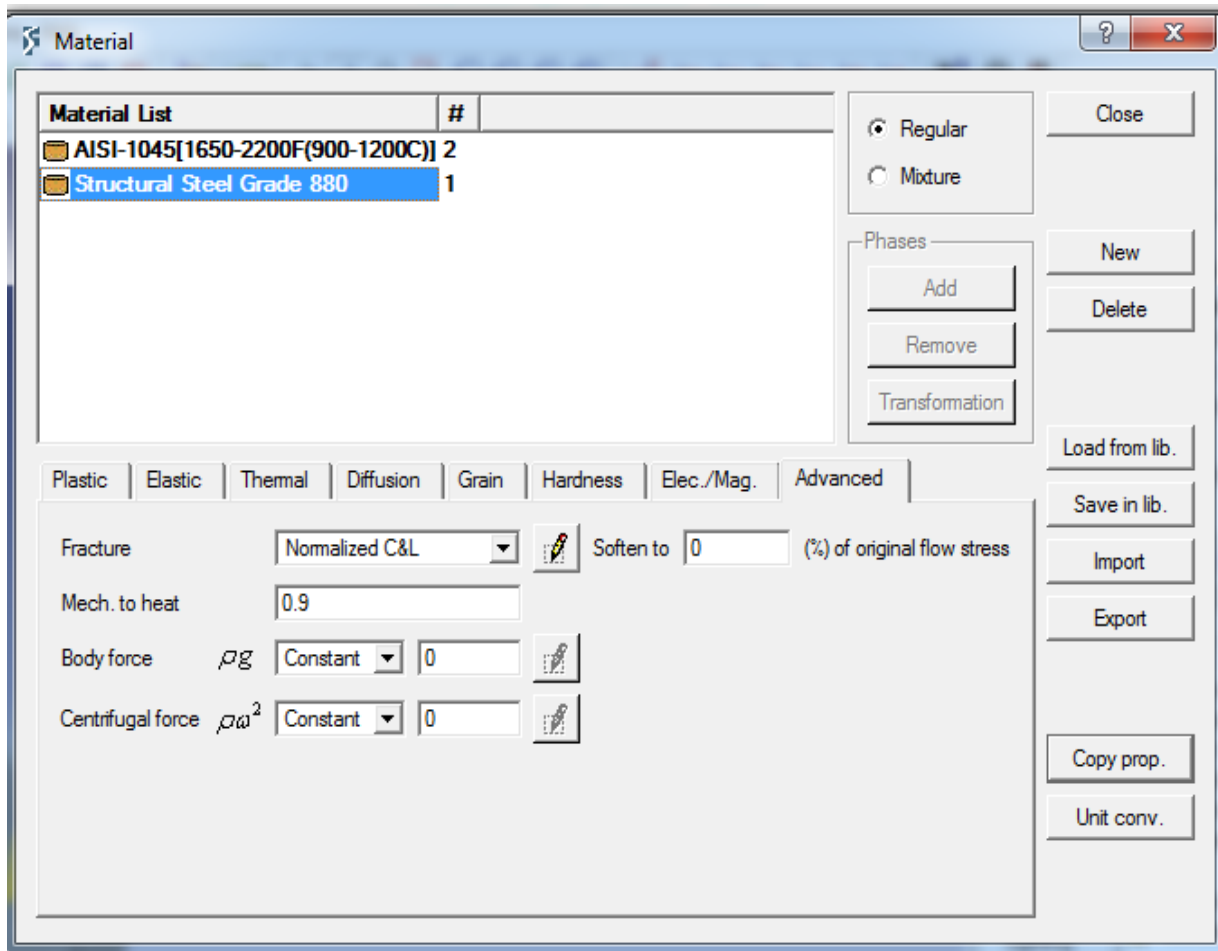


Figure 28: The advanced material window.

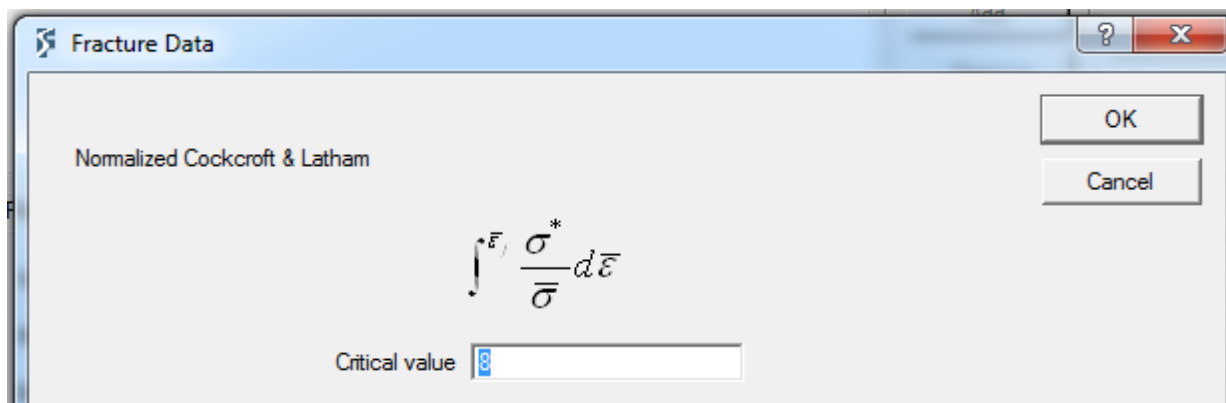


Figure 29: The critical value for fracture

b. Displacement

For small deformation problems only, plots the nodal displacement value. For large deformation, the displacement since the last remesh will be plotted. This variable is primarily intended for die deformation analysis.

c. Strain

Strain is a measure of the degree of deformation in an object. A detailed description of strain is available in any standard text on mechanics of materials, metal forming analysis, or plasticity.

The measure of strain used in large deformation analysis, including DEFORM is *true strain*. For large deformation analysis, it is better to use true strain, which is defined as the sum of a large series of arbitrarily small strain increments. It is frequently useful to have a single characteristic strain value to describe the degree of deformation. DEFORM uses a value common to metal forming analysis known as the effective or Von-Mises strain.

d. Strain Rate

Strain rate is a measure of the rate of deformation with respect to time. The units are strain per second where strain is a dimensionless value. The components of strain rate are defined in the same manner as the components of strain.

e. Stress

Stress is defined as the force acting on a unit area of material. Assume a unit cube of material. Forces (or stresses) acting on the faces of the cube can be resolved into normal (perpendicular to the face) and shear (along the face). Shear stresses can further be resolved into two components along arbitrary orthogonal axes.

f. Velocity

The velocity option plots nodal velocity at each step. Vector plots display magnitude and direction. Magnitude is indicated by vector length and color. Contour plots display only magnitude, where contour color indicates velocity magnitude.

g. Normal Pressure

Normal pressure is the force per unit area on the surface of an object. This is computed on the surface of slave objects. The range of values is from no stress to compressive stress. Tension cannot be maintained without some form of sticking applied between the surfaces.

h. Temperature

The temperature plot displays nodal temperature at each step. [27]

5.2. Results of the Simulation of Designed UIC 60 Rail

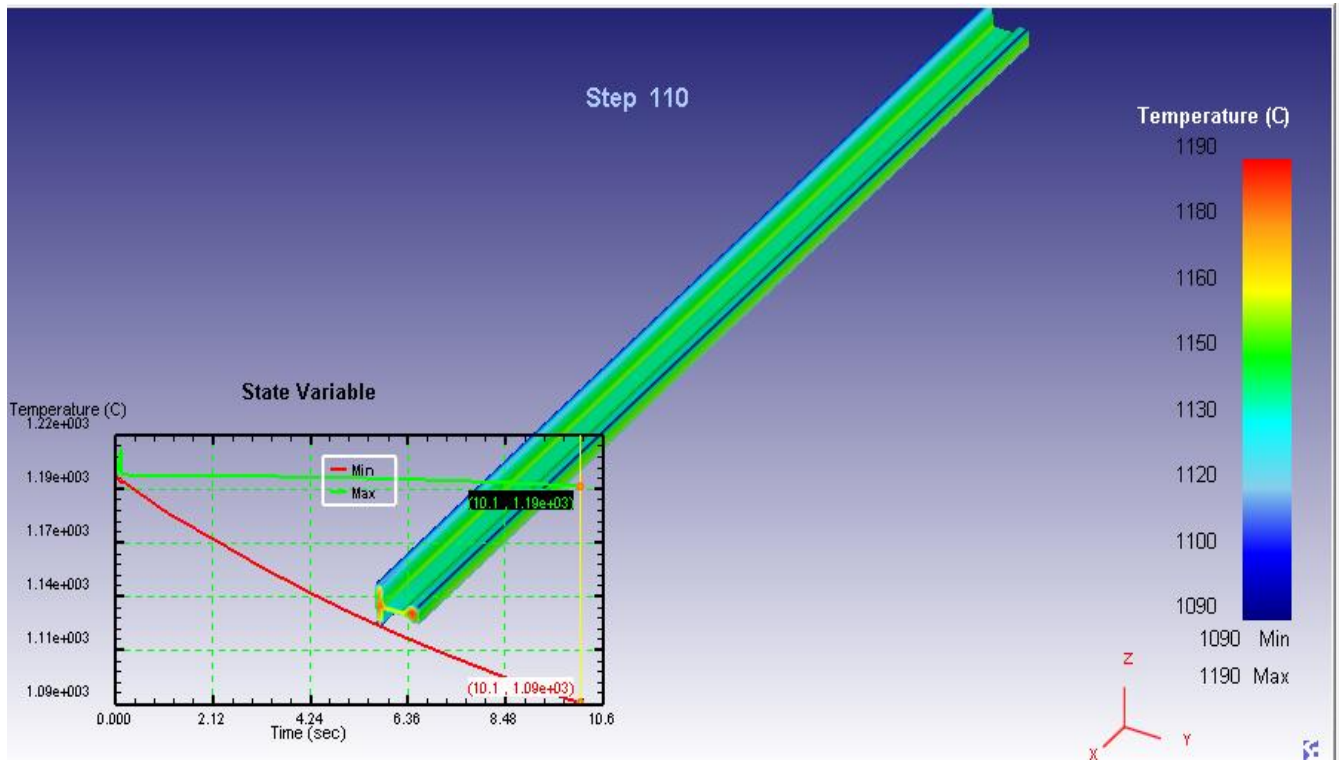


Figure 30. Result of temperature distribution of the rolling process

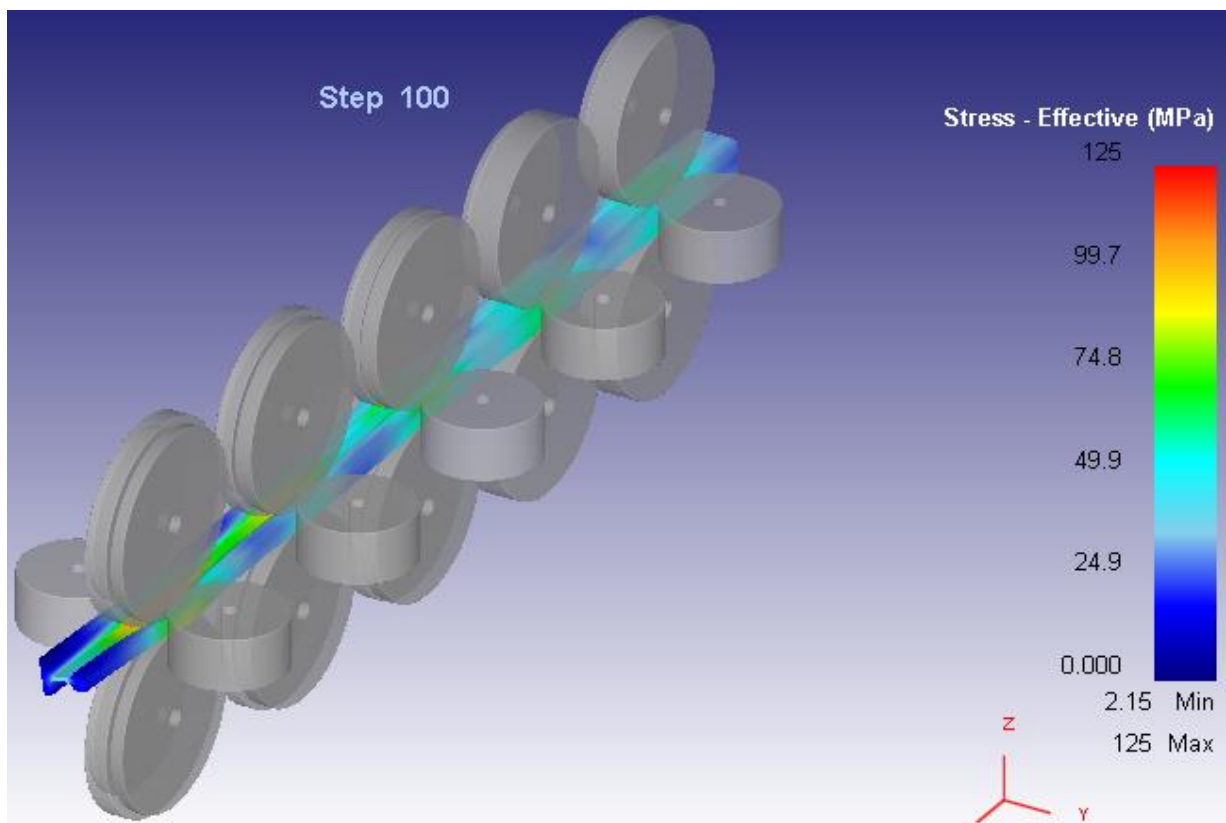


Figure 31. Result of stress induced during rolling

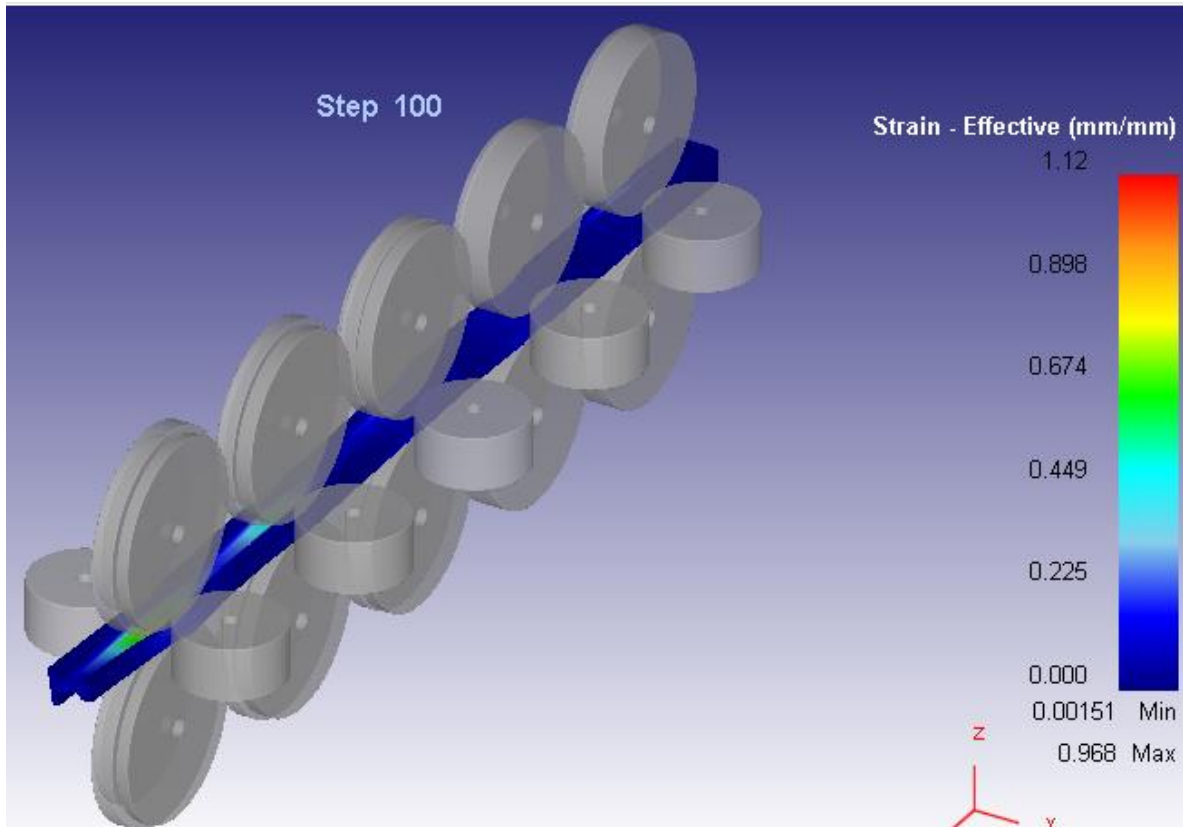


Figure 32. Result of effective strain during rolling process

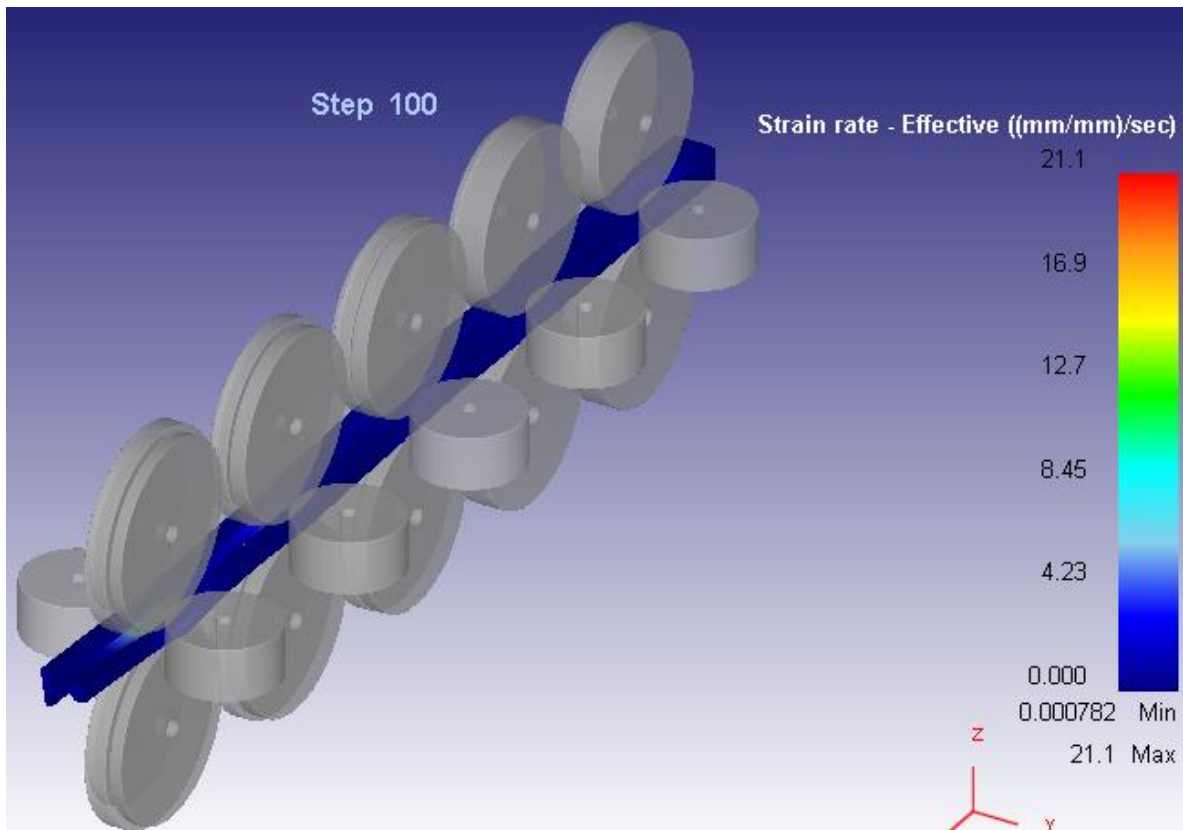


Figure 33. Result of effective strain rate during rolling

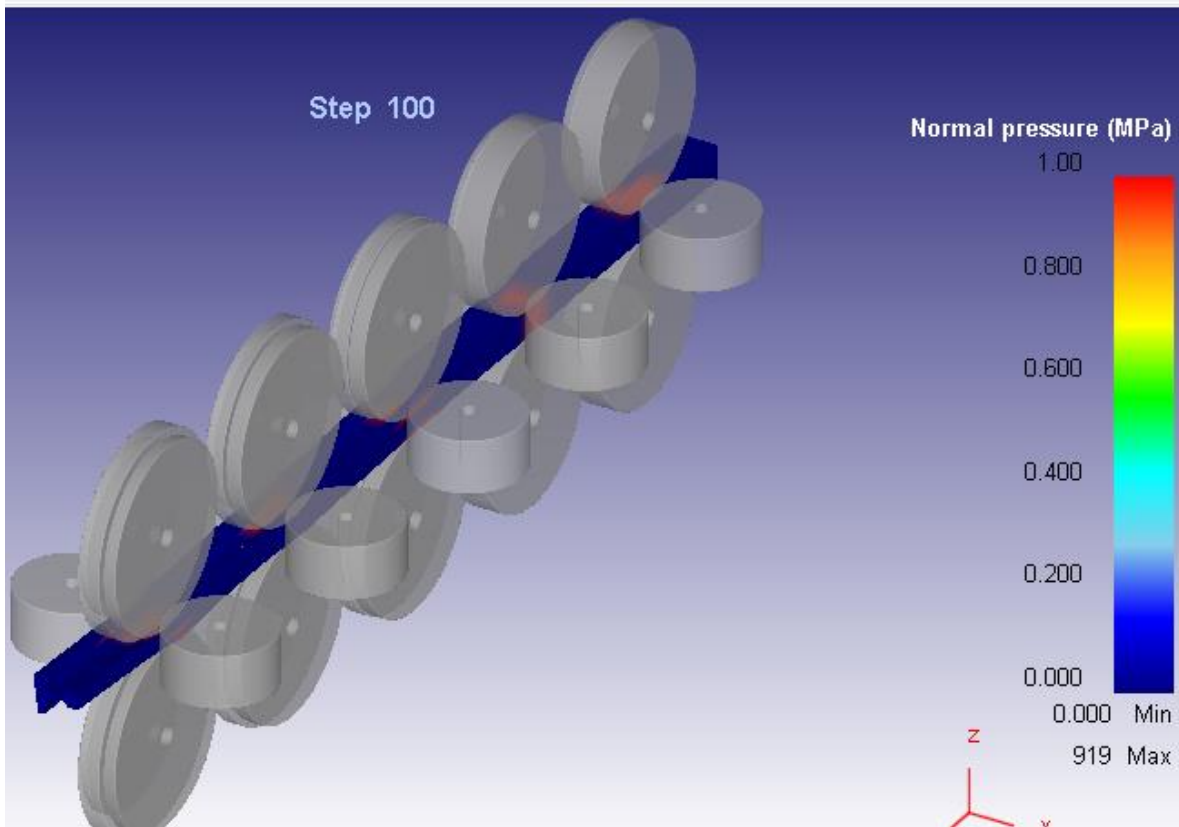


Figure 34. Result of normal pressure induced during rolling

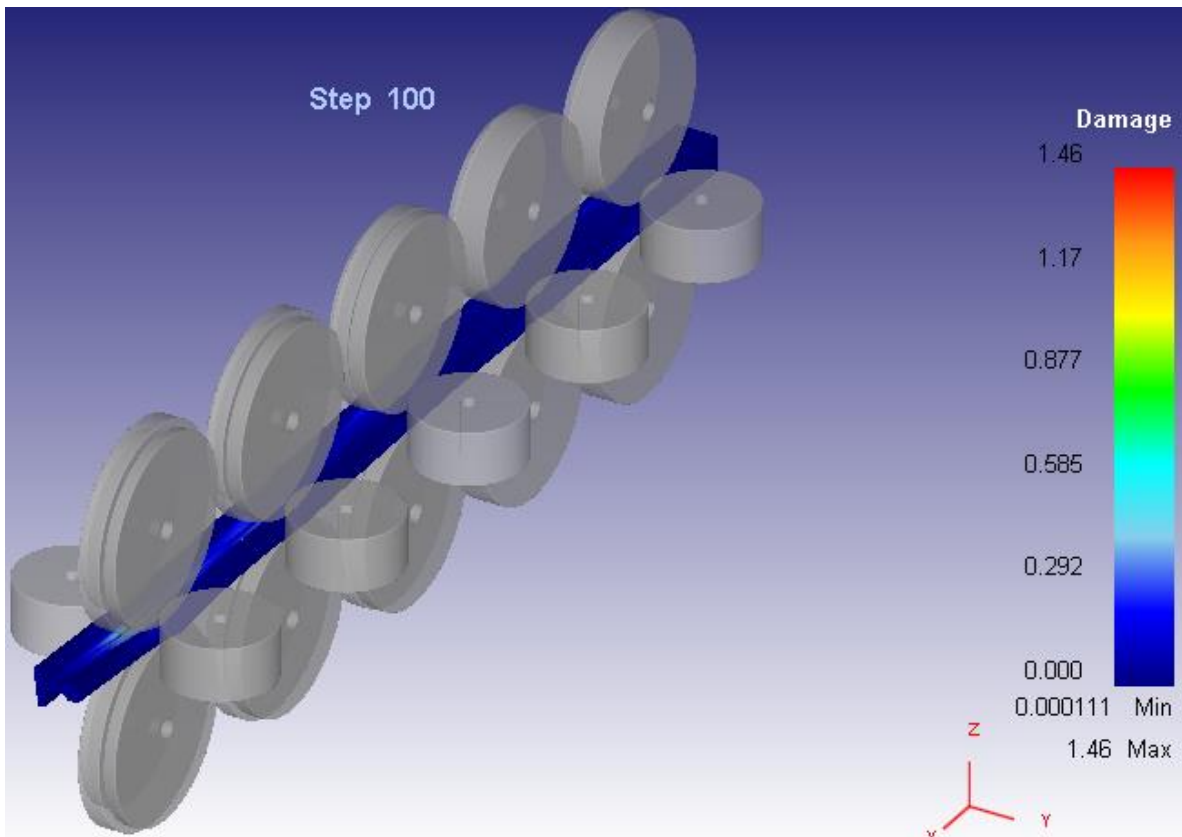


Figure 35. Result of Damage during rolling process

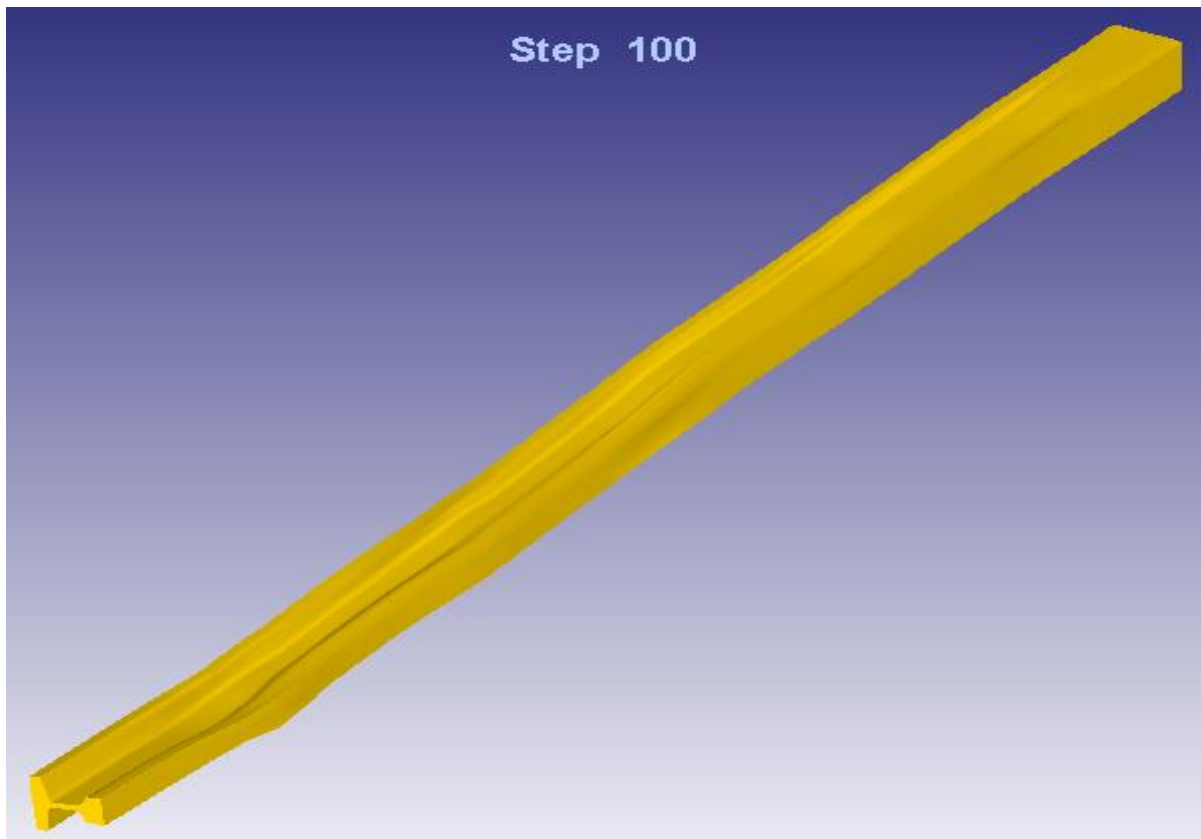


Figure 36. The defects due to high rollers speed and long roller gaps

5.3. Discussion of Results

In thermal analyses, the main load was the initial temperature, constant and equal to 1200 °C on the whole cross-section at the beginning of the process. On the other hand, convective heat transfer boundary conditions plus radiation to the ambient environment were taken into account. The rolls were considered as non-deformable rigid bodies and the heat transfer between them and the stock cross-section was not taken into account. Friction between stock and rolls was modelled using the Coulomb friction law with a friction coefficient, $\mu= 0.244$. According to the simulated result shown in from figure 30 to figure 36, we can see that if the rolling proceeds too fast, the temperature and strain rate can locally reach the limit where the load-carrying capacity of the workpiece is exceeded and defects like bending of the workpiece and cracking evolve.

The initial temperature of the workpiece after leaving the furnace and before entering the rolling operation was 1200°C. But After 10 seconds of rolling, the result of the Deform 3D shown in figure 30 show that the temperature is decrease almost linearly and the maximum temperature of the stock become 1190°C and the minimum temperature become 1090°C. And

also as we can see the result of the DEFORM 3D simulation result in figure 30, the temperature of the rail during rolling is high at center of the cross section and is minimum at the surface boundary.

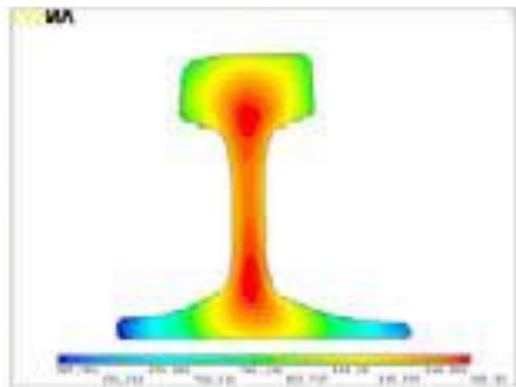


Figure 37. Temperature distribution during rail rolling predicted using Ansys Software

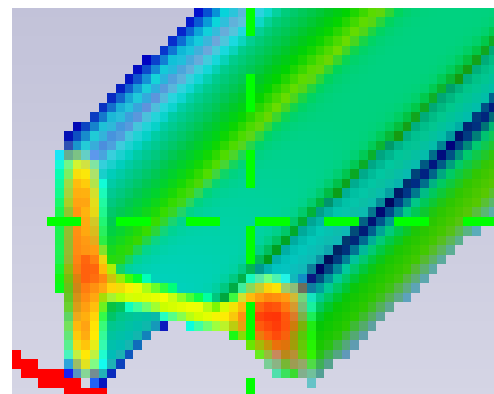


Figure 38. Temperature distribution during rail rolling predicted using DEFORM Software

If we compare the temperature distribution of the rail predicted using the finite element analysis (DEFORM 3D) shown in figure 38 with that of the previous work done using ANSYS software (figure 37) by M. A. Guerrero¹, J. Belzunce, and M^a C. Betegón³, J. Jorge¹, in title “Hot rolling process simulation Application to UIC-60 rail rolling” which is presented on the 4th IASME/WSEAS International Conference on CONTINUUM MECHANICS (CM'09), they are similar. Therefore the design of UIC 60 rail performed using DEFORM 3D is valid

From the simulation result shown in figure 31, we can see that the maximum stress induced during rolling is 125 MPa and it is occurred at the rolling operation when there is a maximum area of reduction. The maximum stresses on the surface of the rail are also located under the contact points of the rollers with the workpiece.

We can also see from the simulation result that the stress induced in each pass varies according to the % reduction in area. It means the stress reduces as the % reduction in area reduces and vice versa.

The critical damage value for the selected rail material is 8 which is described in section 5.1. If we see the simulation result shown in figure 35, the peak value of damage factor is 1.46 which is 18.25% of the critical damage factor.

From figure 34, we can see that the normal pressure during rolling process is maximum at the point where the rollers are in contact with the workpiece.

CHAPTER SIX

CONCLUSION, RECOMMENDATION and FUTURE WORK

From the DEFORM 3D results that are shown and discussed in chapter five and from all the points analyzed in this thesis from chapter 1 to chapter 5, the following conclusion is presented and based on that recommendations and future works are raised.

6.1. Conclusion

The goal of this work was to develop an advanced non-linear finite element model of UIC 60 rail rolling processes that can subsequently be used to analyze the rail rolling process under a series of changing parameters. Many of the mechanisms that govern the hot rolling process are still not fully understood, and there exists a need to provide engineers with comprehensive tools that allow them to design the rolls right the first time, thus reducing the number of trials in the design of the rolls, the amount of material waste, the cost of tooling, and therefore increasing the time that roll designers can spend on engineering as well as the confidence in the manufacturing process and the quality of the final product. All of the above also lead to a reduced time to market, and a lower overall manufacturing cost.

The models developed here, take into account all of the non-linearities present in the rail 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 steel bloom and the steel rolls. So from this thesis, the following things can be concluded.

When we compared the shape predicted with the finite element analyses (DEFORM 3D) and the standard UIC 60 rail, a good shape agreement is found.

The temperature distribution of the rail predicted using the finite element analysis (DEFORM 3D) and that of the previous work predicted by M. A. Guerrero, J. Belzunce, and M^a C. Betegón, J. Jorge¹, are identical. Therefore, the DEFORM 3D software is a reliable tool to predict the distribution of the temperature during hot rolling application.

From the two conformity explained above, we can conclude that the described procedure can be considered as a powerful tool to help experts to roll design. Thus, the number of trials needed to carry out the rolling of a new shape rail would be decreased and also rolling productivity could be increased.

Since the maximum damage factor results from the rolling of UIC 60 rail is in the range of 10% to 20% of the critical damage values, the design is safe from fracture. From this study it can also conclude that if the rolling proceeds too fast, the temperature and strain rate can locally reach the limit where the load-carrying capacity of the workpiece is exceeded and defects like bending of the workpiece evolve. This conditions are also happened when the gap between the rollers are increased.

6.2. Recommendation

From this thesis we can see that manufacturing of rail locally has a lot of economic and social benefits. The long rolled product manufacturing factories found in our country can expand themselves to produce the rail too. By doing this, they can increase their market share and product mix. The other benefit is the foreign currency for buying rail can also be saved, the additional job opportunity is created and the rail way infrastructure is developed. So implementing the rail manufacturing factory in our country is recommended.

6.3. Future Work

The application of finite element techniques to metal forming is still the subject of much research. Researchers are constantly trying to improve their constitutive models of material behavior as well as the FEM portion of their models. The following are areas in which further study can make.

As seen from the previous chapters, the UIC 60 rail is successively designed and simulated using DEFORM-3D finite element software. But this thesis covers only the rolling process. So the research can be extended to construct the models of temperature and microstructure fields of the rail during the air cooling process after rolling, with the distribution regularities of temperature and phase-transformation in air cooling analyzed. And also it is known that repeated bending occurs toward the direction of rail head and rail base during the cooling which can lead to significant bending deformation and residual stress after cooling. The longer the rail is, the more obvious this phenomenon is. So additional research can be done in the area of the Application of Pre-bending Automatic Control of Rail after rolling and cooling operation process are finished. There are more than 8 rolling software, but the design of roll pass of rail in this thesis is performed in only one of them which is DEFORM 3D, therefore, the author recommend to compare other application software like ABAQUS, ANSYS, FORGE and other metal forming software to compare results.

References

- [1] Tulus Tambunan ‘the growth of national steel industry’ Kadin Indonesia – JETRO October 2006
- [2] Central Statistical ‘Agency, manufacturing business survey report’ Jan 2013
- [3] <http://www.erc.gov.et> cited on September 2014
- [4] http://www.addisfortune.com/contact_Addis%20fortune.htm cited on Dec 2014
- [5] Ekelund, S. Jenkontorets Annaler, III, 39-97 (1927).
- [6] Wusatowski, Z. Hot Rolling – a study of draft, spread and elongation. Iron and Steel.
- [7] Hill, R. Private communications with Crum, A.W. on 16 Nov. 1955
- [8] Sparling, L.G.M. Formula for spread in hot flat rolling. Proc. Inst. Mech. Engrs (1961).
- [9] El-Kalay, A.K.E.H.A, and Sparling, L.G.M. Factors affecting friction and their effect up on load, torque, and spread in hot rolling. Journal of Iron and Steel Institute, 152-163. (1968).
- [10] Helmi, A, & Alexander, J.M, Geometric factors affecting spread in hot rolling of steel. Journal of Iron and Steel Institute, 1110-1117. (1968)
- [11] Beese J.G., Ration of lateral strain to thickness strain during hot rolling of steel slabs. Journal of Iron and Steel Institute, 433-436 (1972)
- [12] Shinokura, T. & Takai, K. A new method for calculating spread in rod rolling. Journal of Applied Metalworking, 94-99. (1982).
- [13] Wooyong Shin. B.S., M.S, ‘Development of techniques for pass design and optimization in the rolling of shapes’. Ohio University 1995
- [14] Akgerman, N., Lahoti, G.D. & Atlan, T. Computer aided roll pass design in rolling of airfoil shapes. Journal of applied metal working, 30-40. (1980).
- [15] Stanislav Riljak. ‘Numerical Simulation of Shape Rolling’ Royal Institute of Technology, Stockholm, Sweden, 2006.
- [16] Lapovok R. and Thomson P.F., ‘ An approach to the optimal design of rolling passes’, Int. J. Mach. Tools Manufact. Vol 37 No 8, pp 1143-1154, 1997.
- [17] Jin. Et. ‘ A three dimensional analysis of universal beam tandem rolling process’. Journal of material processing technology. Pp 59-64, (2000).
- [18] Shin. H.W. Kim, D.W., and Kim, N.A. ‘A study on the rolling of I-section beam’, Int. J. Mach. Tools Manufact. Vol 34 No 2, pp 147-160, 1994.
- [19] Jing, Limei, ‘Rolling mill roll design’ Durham University, (2001)

- [20] Mirable. M, et al 'Application of FEM in hot rolling and deep drawing' National technical university of Athens, 1991
- [21] Roberts William, 'Hot rolling of steel manufacturing engineering and materials processing, (1983).
- [22] Souvik Biswas, 'Simulation of thermos-mechanical deformation in high speed rolling of long steel products', Worcester poly technique institute, September 2003.
- [23] Kevin Francis Kenedy, 'A method for metal deformation and stress analysis in rolling' Ohio state university, 1986.
- [24] Alejandro Rivera Muñiz, 'Non- Linear Finite Element Method Simulation and Modeling of the Cold and Hot Rolling Processes', Virginia Polytechnic Institute and State University, Blacksburg, Virginia, January 8th, 2007
- [25] Light rail track design Hand Book.
- [26] Guerrero¹ M. A., Belzunce² J., Betegón M^a C., 'Hot rolling process simulation. Application to UIC-60 rail rolling', Proceedings of the 4th IASME/WSEAS International Conference on CONTINUUM MECHANICS (CM'09), 2009.
- [27] 'DEFORMth 3D version 10.0 user manual', June 30th, 2009.
- [28] Budynas–Nisbett, 'Shigley's Mechanical Engineering Design, Eighth Edition', 2006.
- [29] Mirjana Filipovic 'Evolution of artificial defects during shape rolling' Royal institute of technology, Stockholm, 2007.
- [30] Tibebe Tesfaye, 'Improvement of Reinforcement Steel Bar Fabrication Process in Walia Steel Industry' Bahirdar University, June 2011
- [31] Kim S.Y., IM Y,-T., 'Three dimensional finite element analysis of non-isothermal shape rolling', Journal of material processing technology 127 pp 57–63, (2002).
- [32] Conny Eriksson, 'Roll pass design for improved flexibility and quality in wire rod rolling', Stockholm, Nov. 2004.
- [33] Betego'n Biempica C., J.J. del Coz Di'az, P.J. Garcı'a Nieto, I. Pen~uelas Sa'nchez. 'Nonlinear analysis of residual stress in a rail by manufacturing processes by FEM', Science Direct, Applied Mathematical Modeling 33 pp 34-53 (2009).
- [34] Sunil G. Janiyani , Prof. P. D. Solanki. 'Simulation of Roll Passes for Section Rolling of Flat-Footed Rail Section with the help of FEA', International Journal of Engineering Research & Technology (IJERT) Vol. 1 Issue 3, May – 2012.
- [35] Saral Dutta. B. Tech. (Hons.), I.I.T., ISP & RMD, SAIL 'HOT ROLLING PRACTICE', 2004.

Appendix of the simulation of of rail

The display window of DEFORM 3D Software is where the rolls and workpiece are viewed and geometric information is displayed. The display window can display the following information depending on the tab selected. The available tabs are:

- **Graphic** – A graphical display of the current project.
- **Summary** – A text summary of the current project, listing process conditions, operation information and current step information.
- **Message** – A text file that gives detailed information about the last simulation run. In general, only the last few lines are of interest to the user.
- **Log** – A text file that gives summary information of the overall progress of the last simulation run. As in the case of the message selection, only the last few lines are generally of interest to the user.

The summary, message and log of the simulation result of UIC 60 Rail rolling is shown below

MESSAGE

Step number is 101

TEMPERATURE CALCULATION FOR STEP: 101

TEMPERATURE ITERATION

ITERATION NUMBER	TEMPERATURE NORM	RELATIVE TEMPERATURE ERROR NORM
1	0.0000000000E+00	0.1801209214E+02
2	0.6898224907E+03	0.2685859254E-01
3	0.6718546014E+03	0.8087511264E-03

TOTAL CPU TIME UP TO THIS STEP = 1.0880 (sec)

SUBTOTAL CPU TIME OF THIS STEP = 1.0880 (sec)

CPU FOR HEAT TRANSFER CALCULATIONS (sec)

NONLINEAR H. T. MATRIX	0.1600	3
LINEAR H. T. MATRIX	0.0000	0
INTERFACE H. T. MTRIX	0.0000	3
GEN INT. ELEMENT	0.0000	0
EQUATION SOLVING	0.8640	3
I/O L. H. T.	0.0000	0
FOR ELEMENT HEAT FLUX	0.0000	1

TEMPERATURE CALCULATION FOR STEP : 102
TEMPERATURE ITERATION
ITERATION TEMPERATURE RELATIVE TEMPERATURE
NUMBER NORM ERROR NORM
1 0.6723474207E+03 0.4098701927E+00
2 0.4829779783E+03 0.1787133054E-01
3 0.4882975642E+03 0.5665907410E-03
TOTAL CPU TIME UP TO THIS STEP = 2.3040 (sec)
SUBTOTAL CPU TIME OF THIS STEP = 1.2160 (sec)
CPU FOR HEAT TRANSFER CALCULATIONS (sec)
NONLINEAR H. T. MATRIX 0.2560 3
LINEAR H. T. MATRIX 0.0000 0
INTERFACE H. T. MTRIX 0.0000 3
GEN INT. ELEMENT 0.0000 0
EQUATION SOLVING 0.9600 3
I/O L. H. T. 0.0000 0
FOR ELEMENT HEAT FLUX 0.0000 1
TEMPERATURE CALCULATION FOR STEP : 103
TEMPERATURE ITERATION
ITERATION TEMPERATURE RELATIVE TEMPERATURE
NUMBER NORM ERROR NORM
1 0.4881411305E+03 0.1678724937E+00
2 0.4287087316E+03 0.3700805250E-02
TOTAL CPU TIME UP TO THIS STEP = 3.0720 (sec)
SUBTOTAL CPU TIME OF THIS STEP = 0.7680 (sec)
CPU FOR HEAT TRANSFER CALCULATIONS (sec)
NONLINEAR H. T. MATRIX 0.0960 2
LINEAR H. T. MATRIX 0.0000 0
INTERFACE H. T. MTRIX 0.0000 2
GEN INT. ELEMENT 0.0000 0
EQUATION SOLVING 0.6400 2
I/O L. H. T. 0.0000 0
FOR ELEMENT HEAT FLUX 0.0000 1
TEMPERATURE CALCULATION FOR STEP : 104
TEMPERATURE ITERATION
ITERATION TEMPERATURE RELATIVE TEMPERATURE
NUMBER NORM ERROR NORM
1 0.4300019356E+03 0.1321887446E+00
2 0.3890324502E+03 0.3016151191E-02
TOTAL CPU TIME UP TO THIS STEP = 3.8720 (sec)
SUBTOTAL CPU TIME OF THIS STEP = 0.8000 (sec)
CPU FOR HEAT TRANSFER CALCULATIONS (sec)
NONLINEAR H. T. MATRIX 0.1280 2
LINEAR H. T. MATRIX 0.0000 0
INTERFACE H. T. MTRIX 0.0000 2
GEN INT. ELEMENT 0.0000 0
EQUATION SOLVING 0.6080 2
I/O L. H. T. 0.0000 0
FOR ELEMENT HEAT FLUX 0.0000 1

TEMPERATURE CALCULATION FOR STEP : 105

TEMPERATURE ITERATION

ITERATION TEMPERATURE RELATIVE TEMPERATURE

NUMBER NORM ERROR NORM

1 0.3900162084E+03 0.1026991876E+00

2 0.3621891911E+03 0.2202511195E-02

TOTAL CPU TIME UP TO THIS STEP = 4.6720 (sec)

SUBTOTAL CPU TIME OF THIS STEP = 0.8000 (sec)

CPU FOR HEAT TRANSFER CALCULATIONS (sec)

NONLINEAR H. T. MATRIX 0.1600 2

LINEAR H. T. MATRIX 0.0000 0

INTERFACE H. T. MTRIX 0.0000 2

GEN INT. ELEMENT 0.0000 0

EQUATION SOLVING 0.6400 2

I/O L. H. T. 0.0000 0

FOR ELEMENT HEAT FLUX 0.0000 1

TEMPERATURE CALCULATION FOR STEP : 106

TEMPERATURE ITERATION

ITERATION TEMPERATURE RELATIVE TEMPERATURE

NUMBER NORM ERROR NORM

1 0.3628527195E+03 0.8115457720E-01

2 0.3428603974E+03 0.1675938715E-02

TOTAL CPU TIME UP TO THIS STEP = 5.4400 (sec)

SUBTOTAL CPU TIME OF THIS STEP = 0.7680 (sec)

CPU FOR HEAT TRANSFER CALCULATIONS (sec)

NONLINEAR H. T. MATRIX 0.0640 2

LINEAR H. T. MATRIX 0.0000 0

INTERFACE H. T. MTRIX 0.0000 2

GEN INT. ELEMENT 0.0000 0

EQUATION SOLVING 0.6720 2

I/O L. H. T. 0.0000 0

FOR ELEMENT HEAT FLUX 0.0000 1

TEMPERATURE CALCULATION FOR STEP : 107

TEMPERATURE ITERATION

ITERATION TEMPERATURE RELATIVE TEMPERATURE

NUMBER NORM ERROR NORM

1 0.3433317277E+03 0.6517601899E-01

2 0.3283389274E+03 0.1301375883E-02

TOTAL CPU TIME UP TO THIS STEP = 6.1120 (sec)

SUBTOTAL CPU TIME OF THIS STEP = 0.6720 (sec)

CPU FOR HEAT TRANSFER CALCULATIONS (sec)

NONLINEAR H. T. MATRIX 0.0960 2

LINEAR H. T. MATRIX 0.0000 0

INTERFACE H. T. MTRIX 0.0000 2

GEN INT. ELEMENT 0.0000 0

EQUATION SOLVING 0.5120 2

I/O L. H. T. 0.0000 0

FOR ELEMENT HEAT FLUX 0.0000 1
 TEMPERATURE CALCULATION FOR STEP : 108
 TEMPERATURE ITERATION
 ITERATION TEMPERATURE RELATIVE TEMPERATURE
NUMBER NORM ERROR NORM
 1 0.3286832896E+03 0.5342238353E-01
 2 0.3169893865E+03 0.1035370268E-02
 TOTAL CPU TIME UP TO THIS STEP = 6.8160 (sec)
 SUBTOTAL CPU TIME OF THIS STEP = 0.7040 (sec)
 CPU FOR HEAT TRANSFER CALCULATIONS (sec)
 NONLINEAR H. T. MATRIX 0.0960 2
 LINEAR H. T. MATRIX 0.0000 0
 INTERFACE H. T. MTRIX 0.0000 2
 GEN INT. ELEMENT 0.0000 0
 EQUATION SOLVING 0.5760 2
 I/O L. H. T. 0.0000 0
 FOR ELEMENT HEAT FLUX 0.0000 1
 TEMPERATURE CALCULATION FOR STEP : 109
 TEMPERATURE ITERATION
 ITERATION TEMPERATURE RELATIVE TEMPERATURE
NUMBER NORM ERROR NORM
 1 0.3172481742E+03 0.4472682788E-01
 2 0.3078083651E+03 0.8438877104E-03
 TOTAL CPU TIME UP TO THIS STEP = 7.4880 (sec)
 SUBTOTAL CPU TIME OF THIS STEP = 0.6720 (sec)
 CPU FOR HEAT TRANSFER CALCULATIONS (sec)
 NONLINEAR H. T. MATRIX 0.0960 2
 LINEAR H. T. MATRIX 0.0000 0
 INTERFACE H. T. MTRIX 0.0000 2
 GEN INT. ELEMENT 0.0000 0
 EQUATION SOLVING 0.5760 2
 I/O L. H. T. 0.0000 0
 FOR ELEMENT HEAT FLUX 0.0000 1
 TEMPERATURE CALCULATION FOR STEP : 110
 TEMPERATURE ITERATION
 ITERATION TEMPERATURE RELATIVE TEMPERATURE
NUMBER NORM ERROR NORM
 1 0.3080080643E+03 0.3820094936E-01
 2 0.3001573853E+03 0.7036066818E-03
 TOTAL CPU TIME UP TO THIS STEP = 8.1600 (sec)
 SUBTOTAL CPU TIME OF THIS STEP = 0.6720 (sec)
 CPU FOR HEAT TRANSFER CALCULATIONS (sec)
 NONLINEAR H. T. MATRIX 0.0960 2
 LINEAR H. T. MATRIX 0.0000 0
 INTERFACE H. T. MTRIX 0.0000 2
 GEN INT. ELEMENT 0.0000 0
 EQUATION SOLVING 0.5440 2
 I/O L. H. T. 0.0000 0
 FOR ELEMENT HEAT FLUX 0.0000 1

PROGRAM STOPPED!
 THE CURRENT TIME
 10.0999904

10.0999904 HAS REACHED THE SPECIFIED LIMIT

NORMAL STOP: The assigned steps have been completed.

SUMMARY

Problem ID: SHAPE_ROLL

Summary Preview Message Log Memo

SHAPE_ROLL
 Version No. : 10000
 Release Date : 06/30/09 Initial Simulation Date : 02/02/15 Current Simulation Date : 02/04/15

Process Condition

- Units : SI
- Step -1 ~ 110

Operation List

- **Operation: 1**
 - Simulation mode : Non-Iso
 - Simulation No : 1
 - No. of Object(s): 37
 - Primary die(Object No.): 2

Step No.	Mesh No.	Stroke	Time	Load X	Load Y	Load Z	Speed X	Speed Y	Speed Z	Volume
-1	2	0	0	--	--	--	0	0	0	5.74672e+07
5	2	0	0.005	0	0	0	0	0	0	5.73737e+07
10	2	0	0.01	0	0	0	0	0	0	5.7471e+07
14	2	0	0.014	0	0	0	0	0	0	5.75584e+07
-15	3	0	0.014	--	--	--	0	0	0	5.76049e+07
15	3	0	0.015	0	0	0	0	0	0	5.75532e+07
20	3	0	0.02	0	0	0	0	0	0	5.76031e+07
25	3	0	0.025	0	0	0	0	0	0	5.76543e+07
30	3	0	0.03	0	0	0	0	0	0	5.77052e+07
35	3	0	0.035	0	0	0	0	0	0	5.7756e+07
40	3	0	0.04	0	0	0	0	0	0	5.78057e+07
45	3	0	0.045	0	0	0	0	0	0	5.78558e+07
48	3	0	0.0479904483331	0	0	0	0	0	0	5.78851e+07
-49	4	0	0.0479904483331	--	--	--	0	0	0	5.79646e+07
50	4	0	0.0499904483331	0	0	0	0	0	0	5.78662e+07
55	4	0	0.0549904483331	0	0	0	0	0	0	5.7878e+07
60	4	0	0.0599904483331	0	0	0	0	0	0	5.78956e+07
65	4	0	0.0649904483331	0	0	0	0	0	0	5.79111e+07
70	4	0	0.0699904483331	0	0	0	0	0	0	5.79242e+07
75	4	0	0.0749904483331	819.04	6780.87	7016.74	0	0	0	5.79385e+07
80	4	0	0.0799904483331	1106.67	10816.3	12915.2	0	0	0	5.79535e+07
81	4	0	0.0809904483331	947.67	10892.1	13251.3	0	0	0	5.79566e+07
-82	6	0	0.0809904483331	--	--	--	0	0	0	5.80131e+07
85	6	0	0.0849904483331	0	0	0	0	0	0	5.8e+07
90	6	0	0.0899904483331	3757.95	5478.78	7995.54	0	0	0	5.80501e+07
95	6	0	0.0949904483331	4045.35	10123.7	12889.6	0	0	0	5.81039e+07
100	6	0	0.0999904483331	3974.91	13220.9	15171.4	0	0	0	5.81302e+07

- **Operation: 2**
- Simulation mode : Heat-Transfer
- Simulation No : 2
- No. of Object(s): 1
- Primary die(Object No.): 1

Step No.	Mesh No.	Stroke	Time	Load X	Load Y	Load Z	Speed X	Speed Y	Speed Z	Volume
-101	7	0	0.0999904483331	--	--	--	0	0	0	3.36825e+07
102	7	0	2.09999044833	0	0	0	0	0	0	3.36825e+07
104	7	0	4.09999044833	0	0	0	0	0	0	3.36825e+07
106	7	0	6.09999044833	0	0	0	0	0	0	3.36825e+07
108	7	0	8.09999044833	0	0	0	0	0	0	3.36825e+07
110	7	0	10.0999904483	0	0	0	0	0	0	3.36825e+07

Current Step Information

- Operation No 1 : Multi-Stand-Shape-Rolling (1)
- Mesh No : 2
- Step No :-1
- Number of object(s) : 37
- Object 1 : Workpiece
 - Type : Plastic
 - Mesh : Elements 4104 , Nodes : 5550
 - Material : AISI-1045[1650-2200F(900-1200C)]
- Object 2 : Roll1
 - Type : Rigid
 - Primary die
 - Geometry : Polygons 26280 , Points : 13140
- Object 3 : Roll2
 - Type : Rigid
 - Geometry : Polygons 23400 , Points : 11700
- Object 4 : Roll3
 - Type : Rigid
 - Geometry : Polygons 26280 , Points : 13140
- Object 5 : Roll4
 - Type : Rigid
 - Geometry : Polygons 22680 , Points : 11340
- Object 6 : Roll5
 - Type : Rigid
 - Geometry : Polygons 26280 , Points : 13140

- Object 7 : Roll6
 - Type : Rigid
 - Geometry : Polygons 22680 , Points : 11340
- Object 8 : Roll7
 - Type : Rigid
 - Geometry : Polygons 26280 , Points : 13140
- Object 9 : Roll8
 - Type : Rigid
 - Geometry : Polygons 26280 , Points : 13140
- Object 10 : Roll9
 - Type : Rigid
 - Geometry : Polygons 26280 , Points : 13140
- Object 11 : Roll10
 - Type : Rigid
 - Geometry : Polygons 21240 , Points : 10620
- Object 12 : Roll11
 - Type : Rigid
 - Geometry : Polygons 26280 , Points : 13140
- Object 13 : Roll12
 - Type : Rigid
 - Geometry : Polygons 23400 , Points : 11700
- Object 14 : Roll13
 - Type : Rigid
 - Geometry : Polygons 26280 , Points : 13140

- Object 15 : Roll14
 - Type : Rigid
 - Geometry : Polygons 26280 , Points : 13140
- Object 16 : Roll15
 - Type : Rigid
 - Geometry : Polygons 26280 , Points : 13140
- Object 17 : Roll16
 - Type : Rigid
 - Geometry : Polygons 22680 , Points : 11340
- Object 18 : Roll17
 - Type : Rigid
 - Geometry : Polygons 26280 , Points : 13140
- Object 19 : Roll18
 - Type : Rigid
 - Geometry : Polygons 26280 , Points : 13140
- Object 20 : Roll19
 - Type : Rigid
 - Geometry : Polygons 23400 , Points : 11700
- Object 21 : Roll20
 - Type : Rigid
 - Geometry : Polygons 26280 , Points : 13140
- Object 22 : Roll21
 - Type : Rigid
 - Geometry : Polygons 22680 , Points : 11340

- Object 24 : Roll23
 - Type : Rigid
 - Geometry : Polygons 26280 , Points : 13140
- Object 25 : Roll24
 - Type : Rigid
 - Geometry : Polygons 21960 , Points : 10980
- Object 26 : Roll25
 - Type : Rigid
 - Geometry : Polygons 23400 , Points : 11700
- Object 27 : Roll26
 - Type : Rigid
 - Geometry : Polygons 26280 , Points : 13140
- Object 28 : Roll27
 - Type : Rigid
 - Geometry : Polygons 21960 , Points : 10980
- Object 29 : Roll28
 - Type : Rigid
 - Geometry : Polygons 23400 , Points : 11700
- Object 30 : Roll29
 - Type : Rigid
 - Geometry : Polygons 26280 , Points : 13140
- Object 31 : Roll30
 - Type : Rigid
 - Geometry : Polygons 26280 , Points : 13140

- Object 32 : Roll31
 - Type : Rigid
 - Geometry : Polygons 23400 , Points : 11700
- Object 33 : Roll32
 - Type : Rigid
 - Geometry : Polygons 26280 , Points : 13140
- Object 34 : Roll33
 - Type : Rigid
 - Geometry : Polygons 21240 , Points : 10620
- Object 35 : Roll34
 - Type : Rigid
 - Geometry : Polygons 23400 , Points : 11700
- Object 36 : Roll35
 - Type : Rigid
 - Geometry : Polygons 26280 , Points : 13140
- Object 37 : Roll36
 - Type : Rigid
 - Geometry : Polygons 26280 , Points : 13140

LOG

```

*** INFO: Begin of Solution for Run# 1
Starting time is:Mon Feb 02 11:02:07
*** INFO: End of Solution for Run# 1
FEM MESSAGE:
*** INFO: Remeshing at Step -82

*** INFO: Extract Border of Object '1' for Run# 5

*** INFO: Generate Mesh for Run# 5
mesh size
Info: Reading Mesh size
mesh size =
Info: Reading DEF_BRK2.INI
input
Info: Reading the Result file
Info: Check the topology!
Info: Establish FEM solid Structure for Obj# 1
Info: Extract FEM surface for Obj#: 1
Info: Number of FEM surface Polygons Extracted: 2836
Info: Establish Surface Structure for Obj#: 1
    
```

Node list = 6 2 3 5
Info: Remesh the cross section!
... reading from file NBCD.DAT
... boundary conditions
... symmetry conditions
... reading from file NBCD.DAT
... boundary conditions
... symmetry conditions
... die coordinates
... die connectivity
section containing 5089
Reading die geometry ...
Info: Establish Surface Structure for Obj#: 2
Info: Establish Surface Structure for Obj#: 3
Info: Establish Surface Structure for Obj#: 4
Info: Establish Surface Structure for Obj#: 5
Info: Establish Surface Structure for Obj#: 6
Info: Establish Surface Structure for Obj#: 7
Info: Establish Surface Structure for Obj#: 8
Info: Establish Surface Structure for Obj#: 9
Info: Establish Surface Structure for Obj#: 10
Info: Establish Surface Structure for Obj#: 11
Info: Establish Surface Structure for Obj#: 12
Info: Establish Surface Structure for Obj#: 13
Info: Establish Surface Structure for Obj#: 14
Info: Establish Surface Structure for Obj#: 15
Info: Establish Surface Structure for Obj#: 16
Info: Establish Surface Structure for Obj#: 17
Info: Establish Surface Structure for Obj#: 18
Info: Establish Surface Structure for Obj#: 19
Info: Establish Surface Structure for Obj#: 20
Info: Establish Surface Structure for Obj#: 21
Info: Establish Surface Structure for Obj#: 22
Info: Establish Surface Structure for Obj#: 23
Info: Establish Surface Structure for Obj#: 24
Info: Establish Surface Structure for Obj#: 25
Info: Establish Surface Structure for Obj#: 26
Info: Establish Surface Structure for Obj#: 27
Info: Establish Surface Structure for Obj#: 28
Info: Establish Surface Structure for Obj#: 29
Info: Establish Surface Structure for Obj#: 30
Info: Establish Surface Structure for Obj#: 31
Info: Establish Surface Structure for Obj#: 32
Info: Establish Surface Structure for Obj#: 33
Info: Establish Surface Structure for Obj#: 34
Info: Establish Surface Structure for Obj#: 35
Info: Establish Surface Structure for Obj#: 36
Info: Establish Surface Structure for Obj#: 37
Info: Checking Node penetration
Info: Node 1 of Object 1 is inside Object 34

Node 1 Old coord. -8.9791317 26.1770261 3721.4049227
New coord. -8.9791317 26.1770261 3721.4049227
Info : Node 5191 Has penetrated the die
Info: Node 1 of Object 1 is inside Object 34
Node 1 Old coord. -21.9233484 26.9307747 3721.3835222
New coord. -22.0204417 26.7043627 3721.4298939
Info : Node 5183 Has penetrated the die
Info: Node 1 of Object 1 is inside Object 11
Node 1 Old coord. -116.4938805 28.8933475 3721.1708081
New coord. -116.2453764 28.7381959 3721.2903318
Info : Node 5106 Has penetrated the die
Info: Checking Edge penetration
Info: Node 1 of Object 1 is inside Object 34
Node 1 Old coord. -15.4997867 26.4406944 3721.3942224
New coord. -15.4997867 26.1770354 3721.3939967
Info: Node 1 of Object 1 is inside Object 11
Node 1 Old coord. -120.8832862 27.3602037 3721.1970592
New coord. -120.8470457 26.1834124 3721.2135019
Area = 7814.18751329180
2D GEO generation
Done 2D meshing
Info: Profile Mimimization!
Old Profile : 1425
New Profile : 1247
Info : Smoothing is carried out!
Info: Check bad element !
Info: Smoothing is being Done!
Info: Check Subdivision
Info: Output SCRATCH.KEY!
Info: Mesh contains 0 sections, and
there are 137 elements per section
Info: Check Memory leak!
236934 -236934
Info: The net Memory allocation is 0
Brick remeshing is successful.
Brick remeshing is successful.

*** INFO: Interpolate Data for Run# 5

*** INFO: Prepare Input Data for Run# 5

Ending time is:Wed Feb 04 12:32:20

Remesh elapsed time for Run#5 : 38 Seconds (38 Total Seconds)
The total Remesh elapsed time : 2 Minutes 39 Seconds (159 Total Seconds)

*** INFO: Begin of Solution for Run# 5

Starting time is:Wed Feb 04 12:32:20

*** INFO: End of Solution for Run# 5

FEM MESSAGE:

NONLINEAR H. T. MATRIX	0.4480	8
LINEAR H. T. MATRIX	0.0000	0
INTERFACE H. T. MTRIX	0.0960	8
GEN INT. ELEMENT	0.0000	4
EQUATION SOLVING	2.1760	8
I/O L. H. T.	0.0000	0
FOR ELEMENT HEAT FLUX	0.0000	4

NORMAL STOP: The assigned steps have been completed.

Ending time is:Wed Feb 04 19:30:13

FEM elapsed time for Run#5 : 6 Hours 57 Minutes 53 Seconds (25073 Total Seconds)
The total FEM elapsed time : 2 Days 8 Hours 25 Minutes 27 Seconds (203127 Total Seconds)

*** INFO: Simulation Module Indicates End of Simulation

*** INFO: End of Automatic Remeshing Run -- Bye###
Total Number of Runs = 5

The total FEM elapsed time : 2 Days 8 Hours 25 Minutes 27 Seconds (203127 Total Seconds)

The total Remesh elapsed time : 2 Minutes 39 Seconds (159 Total Seconds)

The total simulation elapsed time : 2 Days 8 Hours 28 Minutes 6 Seconds (203286 Total Seconds)

MASTER FILE PRESENT

MULTIPLE OPERATION: CURRENT SIMULATION NO = 2

MASTER FILE SUCCESSFULLY PARSED

Multiple operation keyword file reading

*** Direct DB Writing Scheme On

Checking Input Data

INFO : Checking simulation controls

INFO : Checking material properties

INFO : Checking inter-material data
INFO : Checking object data
INFO : Checking inter-object data
WARNING: No Inter-Object Relation Defined
INFO : Input data has no errors
CHK_VOL.INI doesn't exist
INFO : DEFORM Database Generated
Multiple operation keyword processedC:\Program
Files\SFTC\DEFORM\v10.0\3D\DEF_ARM.COM SHAPE_ROLL B

*** INFO: Begin of Solution for Run# 1

Starting time is:Wed Feb 04 19:30:23

*** INFO: End of Solution for Run# 1

FEM MESSAGE:

INTERFACE H. T. MTRIX	0.0000	2
GEN INT. ELEMENT	0.0000	0
EQUATION SOLVING	0.5440	2
I/O L. H. T.	0.0000	0
FOR ELEMENT HEAT FLUX	0.0000	1

PROGRAM STOPPED!

THE CURRENT TIME 10.0999904 HAS REACHED THE SPECIFIED LIMIT
10.0999904

NORMAL STOP: The assigned steps have been completed.

Ending time is:Wed Feb 04 19:30:36

FEM elapsed time for Run#1 : 13 Seconds (13 Total Seconds)

The total FEM elapsed time : 13 Seconds (13 Total Seconds)

*** INFO: Simulation Module Indicates End of Simulation

*** INFO: End of Automatic Remeshing Run -- Bye###

Total Number of Runs = 1

The total FEM elapsed time : 13 Seconds (13 Total Seconds)

The total Remesh elapsed time : 0 Second (0 Total Seconds)

The total simulation elapsed time : 13 Seconds (13 Total Seconds)

MASTER FILE PRESENT

MULTIPLE OPERATION COMPLETED.