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Format for the Final- week Report*

Name of the candidate	:	Yogesh Mahendra Nemade
Application Registration no.	:	ENGS1516
Date of Commencement of work	:	24 May 2021
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Project title	:	Design and Simulation of Material Flow during Non-Uniform Deformation of Alloys

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Design and Simulations of Material Flow During Non-Uniform Deformation of Alloys

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Contents

Abstract

A basic finite element model for thermo-mechanical analysis of hot worked bulb bar rolling process has been prepared in DEFORM 3D. The report consists of the details of the model and analysis of results. Fully coupled thermal-stress method has been implemented using implicit approach. The dimensions are taken from British bulb bar and other hypothetical input parameters like dimension, material, roller speeds, and temperatures. The aim is to create a basic model that can be iterated over varying inputs to study the cause and effects of irregularity occurring in the rolled product.

Keywords:

Finite Element Mechanics, shape rolling, bulb bar, flow stress, hot rolling.

Abbreviations

Table 1: Abbreviations

FEM	Finite Element Mechanics
CG	Conjugate-Gradient
S	Forward Slip
JC	Johnson & Cook model

1. Introduction

1.1 Background

Bulb flats are a hot-rolled piece of steel with one end having a "stem" sticking out. Bulb flats are the most cost-effective, efficient and corrosion-resistant solution for plate stiffening requirements.

Advantages of bulb flats are:

1. The unique shape of a bulb flat distributes steel to maximise resistance to buckling. This results in a more efficient strength to weight ratio compared with other stiffeners such as flat bars or structural angles.
2. The compact shape of a bulb flat offers easy access for welding and painting.
3. The asymmetric bulb flat shape lends itself to simplified collar connection when compared to alternative stiffeners such as 'T's and angles.
4. The rounded profile of a bulb flat, with no sharp corners, assists effective and efficient painting.

Figure 1: Bulb bar

5. Bulb flats can also reduce coating material costs because they have a smaller surface area than other stiffeners with the same section modulus.

6. Paint degradation and the build-up of corrosive debris is also reduced, extending life performance.

Recognition of the benefits which bulb flats provide is resulting in increased usage for ships (ship hull, ballast tanks, cargo holds), bridges (box and plate girder, steel decks and expansion joints) and construction work.

Figure 2: Application of bulb flats in construction

1.2 Problem Statement

We have been working on designing roll pass for making bulb bar using hot rolling. The rolling of bulb bars involves difficulties that are associated with a great difference in thickness between the bulb of the bar and the relatively little thickness of its flat part. This feature might contribute to the unstable behaviour of the band during hot rolling.

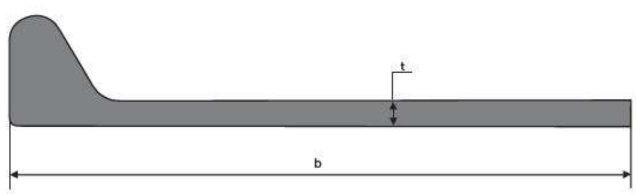


Figure 3: Cross-section of a bulb bar

It has been found from industrial tests carried out that a non-uniform distribution of mechanical properties occurs on the cross-section of bars produced by the conventional method. The difference in the value of yield point between the bulb and the flat of the bar may reach 35%.

The simulation process of hot rolling was carried out using three-dimensional numerical simulation based on the **DEFORM-3D** software package, which used embedded pre-processor, post-processor, and the finite element method for solving problems. The widespread use of this method is largely due to a simple physical interpretation of its main computational operations, great geometric flexibility and applicability to a wide class of partial differential equations. It allows one to quite accurately describe the curvilinear boundaries of the domain of definition of the solution and the boundary conditions.

2.Literature Review

2.1 Rolling

In metalworking, rolling is a metal forming process in which metal stock is passed through one or more pairs of rolls to reduce the thickness, to make the thickness uniform, and/or to impart a desired mechanical property. The concept is similar to the rolling of dough. Rolling is classified according to the temperature of the metal rolled.

1. **Hot rolling**: Hot rolling is a metalworking process in which metal is heated above the recrystallization temperature to plastically deform it in the working or rolling operation. This process is used to create shapes with the desired geometrical dimensions and material properties while maintaining the same volume of metal. The hot metal is passed between two rolls to flatten it, lengthen it, reduce the cross-sectional area and obtain a uniform thickness.

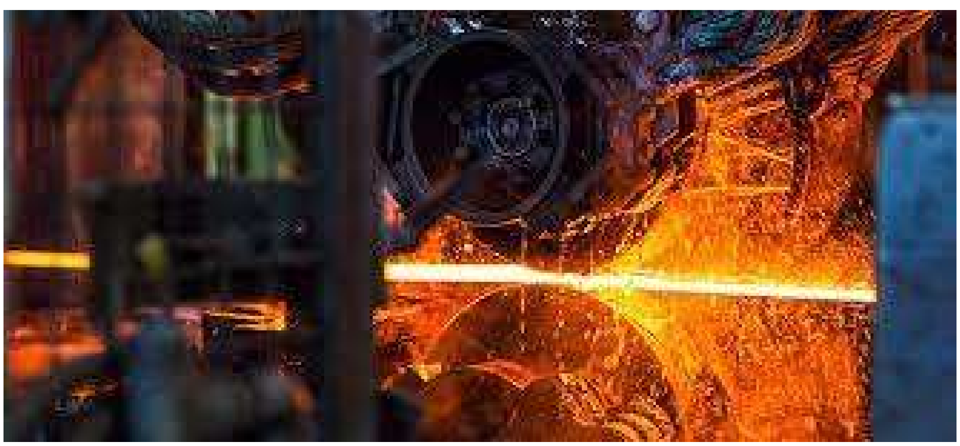


Figure 4: Hot rolled steel

2. Cold rolling: Cold rolling is a technique where a metal strip or sheet is passed between two rollers and then squeezed and compressed. The level of strain present determines the properties and hardness of the finished material. This process is widely used for

surface finish and high-quality dimensional accuracy, which can help prevent material damage and corrosion.

Figure 5: Cold rolling pass

2.2 Flat rolling and its analysis

Flat rolling involves the rolling of slabs, strips, sheets and plates work parts of rectangular section in which the width is greater than the thickness. The flat section of the bulb bar undergoes flat rolling. The reduction in thickness is called as **draft** [10]:

$$d = h_0 - h_f = 2\,R(1 - \cos\theta)$$

Where d= draft, t_0= starting thickness, t_f = final thickness. R= roll radius and θ= angle of bite. Draft can be expressed as a fraction of the starting thickness, called **reduction**:

$$r = \frac{d}{h_0}$$

Where r = reduction. The maximum possible draft can be shown as a function of the roll radius (R) and the coefficient of friction (μ) between the billet and the roll. The relationship can be shown through the following equation:

$$d_{max} = \mu^2 R$$

Since the material is not removed volume is constant throughout the process i.e.

$$h_0 w_0 L_0 = h_f w_f L_f$$

Similarly, before and after volume rates of material flow must be the same, so the before and after velocities can be related as:

$$h_0 w_0 V_0 = h_f w_f V_f$$

Considering the surface speed of the rolls as V_r and the velocity of the billet increases from its entry value V_0as it moves through the roll gap (fig. 6). The velocity of the billet will be highest at the exit and is denoted as V_f. The metal accelerates in the roll gap in the same manner as an incompressible fluid flowing through a converging channel.

As the surface speed of the rigid roll is constant, relative sliding occurs between the roll and the billet along the arc of contact (L). At one point along the contact length (called the **neutral point or no-slip point**) the velocity of the billet is the same as that of the roll. To the left of this point, the roll moves faster than the billet; to the right of this point, the billet moves faster than the roll. Consequently, the frictional forces-which oppose motion between two sliding bodies-act on the billet. On either side of this point, slipping and friction occur between roll and billet. The amount of slip between the rolls and the billet can be measured by means of the **forward slip**, a term used in rolling that is defined:

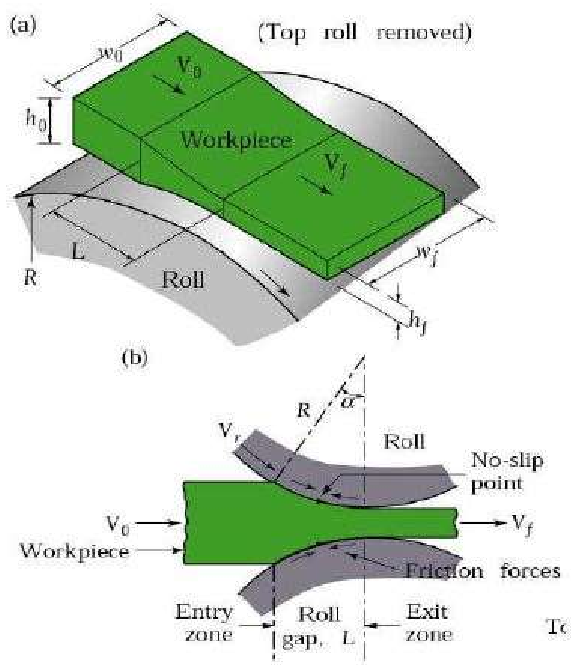


Figure 6: Billet undergoing flat rolling

$$S = \frac{V_f - V_r}{V_r}$$

Where s = forward slip; V_f= final velocity, and V_r= roll speed.

2.3 Mathematical Model

The problem is a transient problem with varying temperature in the billet. So accordingly, the differential equation for governing the motion of a material point at time t [2,3]:

$$\nabla\sigma + b = \rho\ddot{u}\ (x, y, t)$$

Where σ is the Cauchy stress tensor, b is the body force per unit volume, ρ is the density of the element and u *(x, y)* is the time dependent displacement vector of the material at point *(x, y)*.

To predict the velocity field, virtual work rate principle can be used. It states that for the stress field that is in equilibrium within the body and with applied surface tractions, the work rate inside the deforming body equals the work rate done by the surface tractions for all the velocity fields that are continuous and continuously differentiable (also called as virtual velocity fields) [4].

$$\int_V \sigma_{ij} \frac{\partial \dot{u}_j}{\partial x_i} dV = \int_S F_j \dot{u}_j dS$$

Where σ_{ij} is the stress field that is in equilibrium and $\dot{u}_j$ is any virtual velocity field. V is the volume of the body and S is the surface. Above equation can also be written as,

$$\int_V \sigma_{ij} \, \dot{\varepsilon}_{ij} dV = \int_S F_j \dot{u}_j dS$$

Where $\dot{\varepsilon}_{ij}$ is the strain rate.

In the visco-plastic field, the material can be considered as the isotropic incompressible non-Newtonian fluid [3]. The strains calculated earlier will also have a thermal strain component which is dependent on the temperature change w.r.t time.

The thermo-mechanical process of hot and cold rolling has stress and temperature interdependent in it, their equations need to be fully coupled for accurate results. During rolling process, temperature distribution in the billet can be calculated using the general conduction equation:

$$k \frac{\partial^2 T}{\partial x^2} + k \frac{\partial^2 T}{\partial y^2} + k \frac{\partial^2 T}{\partial z^2} + \dot{Q} = \rho \, c \, \frac{\partial T}{\partial t}$$

Where k is the thermal conductivity of the material, c is the specific heat and $\dot{Q}$ is the volumetric heat generated. In the case of rolling heat generation is majorly because of the deformation. Contribution of heat generated due to friction to the overall heat generated is found to be low [3].

$$\dot{Q} = n \, \sigma \, \varepsilon + \dot{q}_{fric} \qquad \dot{q}_{fric} = |\tau \, v|$$

Where n is the efficiency of conversion of deformation energy to heat, τ is the shear stress and v is the sliding velocity.

Convection takes place from the top surface of the rolled billet while the rolling is in progress.

Thermal boundary conditions are as follows:

At the top surface:

$$-k\frac{\partial T}{\partial y} = h\,(T - T_{amb})$$

At the deformation zone:

$$-k\frac{\partial T}{\partial y} = h\,(T - T_{amb}) - \dot{q}_{fric}$$

3. Methodology

3.1 Simulation controls

3.2.1 Solver

DEFORM uses implicit analysis for its simulations. Lagrangian computation was carried out on the analysis mesh with appropriate boundary conditions for the rolling operation to overcome some of the difficulties faced with Arbitrary Lagrangian-Eulerian (ALE) computation. It is coupled with Conjugate-Gradient (CG) solver to solve the set of equations generated for the problem.

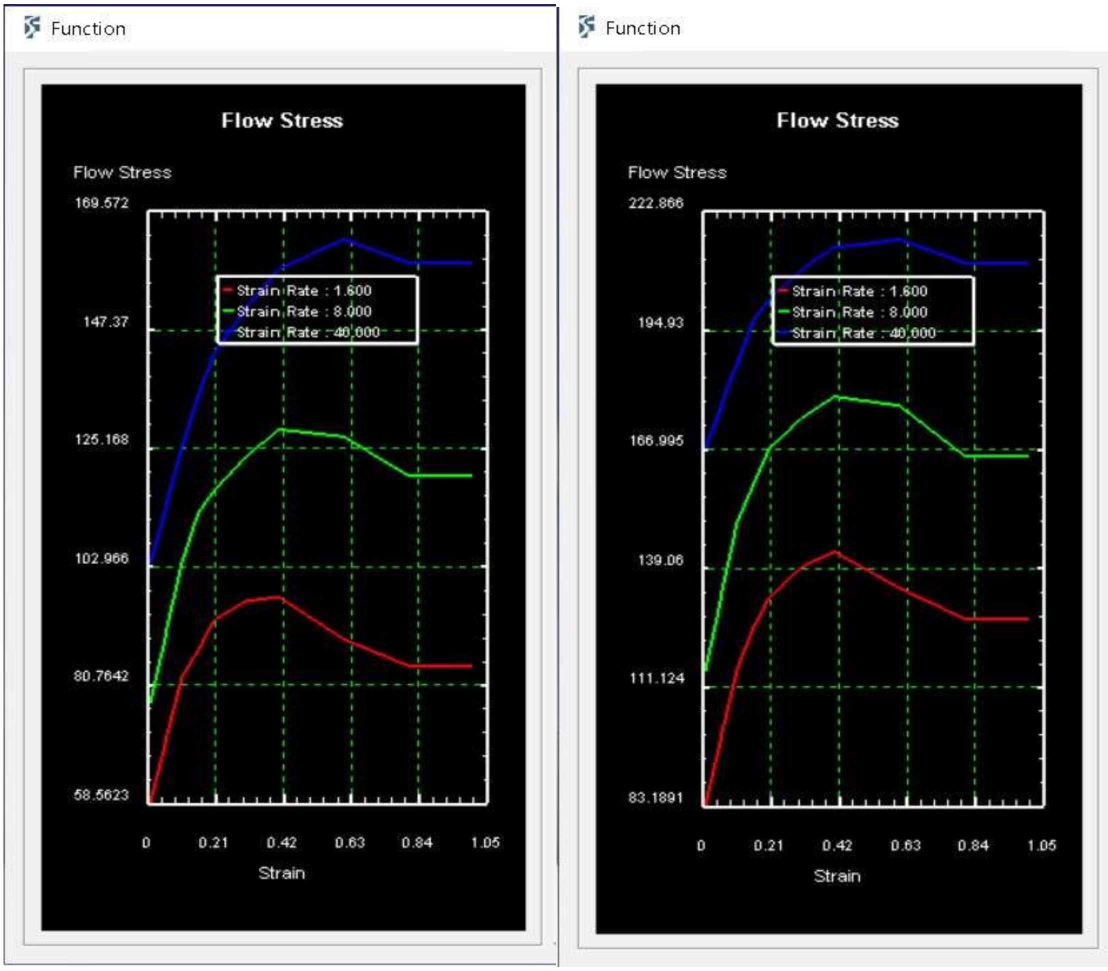
3.2.2 Flow stress

The flow stress, typically denoted as Y_f (or σ_f), is defined as the instantaneous value of stress required to continue plastically deforming a material - to keep it flowing. On a stress-strain curve, the flow stress can be found anywhere within the plastic regime; more explicitly, a flow stress can be found for any value of strain between and including yield point (σ_y) and excluding fracture (σ_F):

$$\sigma_F \leq Y_f \leq \sigma_y.$$

DEFORM uses the model in which flow stress changes as deformation proceeds and usually increases as strain accumulates due to work hardening, although the flow stress could decrease due to any recovery process. In the model, the flow stress for a given material will vary with changes in temperature, T, strain, ε, and strain-rate, $\dot{\varepsilon}$. Therefore, it can be written as some function of those properties:

$$Y_f = f(\varepsilon, \dot{\varepsilon}, T)$$



(a) (b)

Figure 7: Variation of flow stress for AISI-1045(20-1100C) at (a)1100 C and (b)1000 C (SFTC-material data)

3.2.3 Remeshing

One of the qualities of DEFORM 3D is that uses adaptive mesh generation combined with remeshing as a default option. A major problem associated with metal forming operations is large amount of local deformation in the workpiece. This creates more difficulty while studying these operations through simulations and cause computational problems. Added to this the high relative motion between die surface and the deforming material distort the mesh. The advantages of this meshing method include:

1. Adaptive mesh generation helps to create mesh with varying density of elements.
2. Remeshing assign new mesh system to the workpiece after deformation.
3. It also transfers the information (stress, strain rate, temperature, etc.) from old mesh to the new mesh through interpolation.

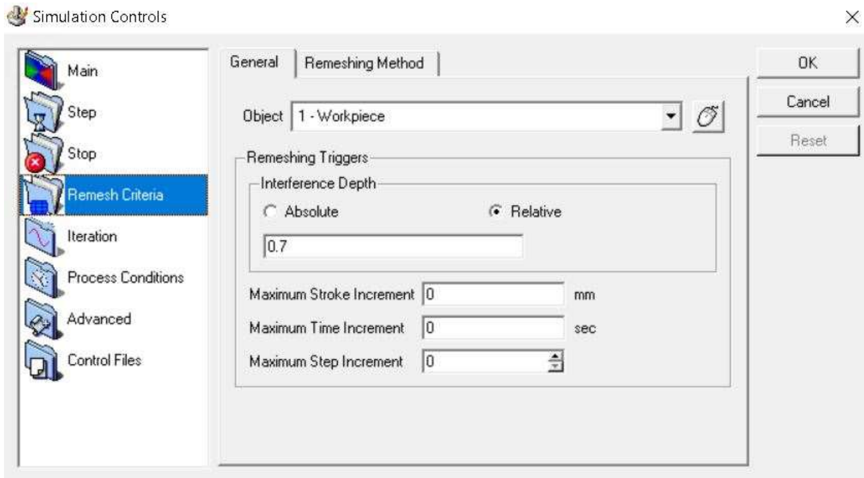
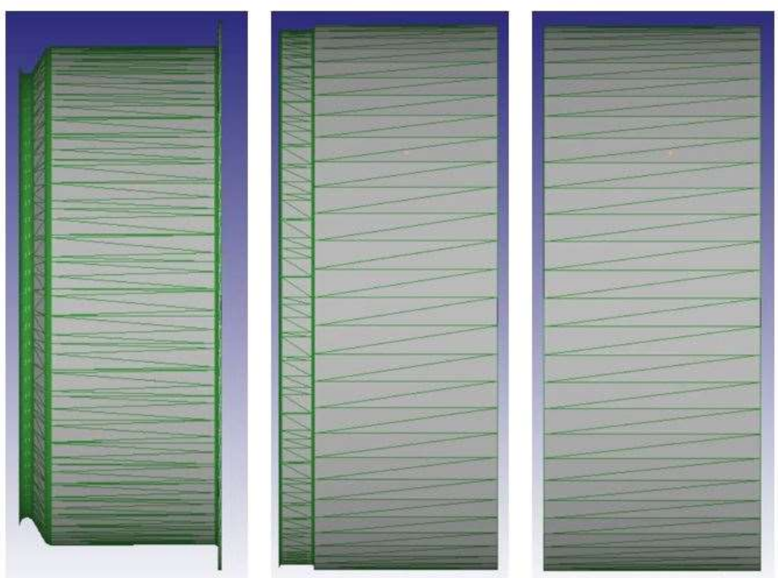


Figure 8: Remeshing in DEFORM 3D

3.2 Model

The assembly comprises of rollers (rigid) and billet (plastic) to create a bulb bar. The rollers are designed to progressively impart the shape to the billet. The dimensions (in mm) are given as:



(a) (b) (c)

Figure 9: (a) grooved top roller, (b) grooved bottom roller till penultimate pass, (c) final bottom roller

1. Roller: radius = 200, width = 160
2. Workpiece: length = 500, width=140, thickness = 80
3. Bulb groove: 160 x 10 British bulb bar [11], bulb height = 22

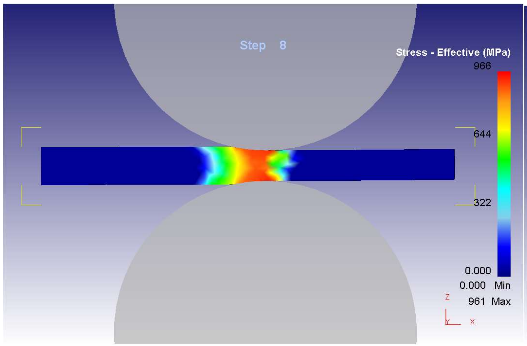
3.3 Boundary conditions

1. Flat rolling:
    a. Heat exchange with environment (30°C) with convection coefficient of 0.05N/sec/mm/C
    b. Initial temperature of billet = 1000°C
    c. Initial temperature of roller = 300 °C
    d. Penalty contact condition with $\mu = 0.3$
    e. Fraction of heat generation due to friction = 0.9
    f. Contact thermal conductance = 2000 N/sec/mm/C
2. Bulb bar rolling:
    a. Heat exchange with environment (30°C) with convection coefficient of 0.05N/sec/mm/C
    b. Displacement = 0 on left face of the billet
    c. Initial temperature of billet = 1000°C
    d. Initial temperature of roller = 400°C
    e. Penalty contact condition with $\mu = 0.3$
    f. Fraction of heat generation due to friction = 0.9
    g. Contact thermal conductance = 2000 N/sec/mm/C

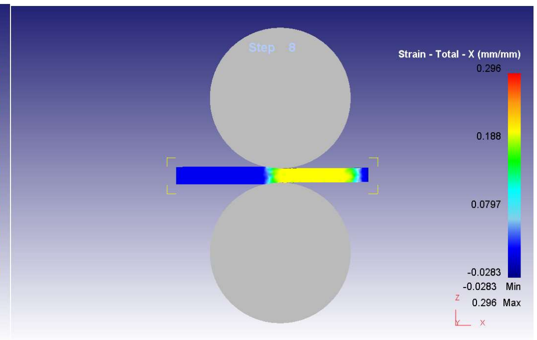
4. Results

Initial analysis was done for cold rolling with 10% reduction in the thickness of the billet. Cold rolling is done under recrystallisation temperature of the metal, this induces high internal stresses in the billet that can be seen in the results. The maximum stress obtained on the billet was around 966 MPa (fig. 10(a)).

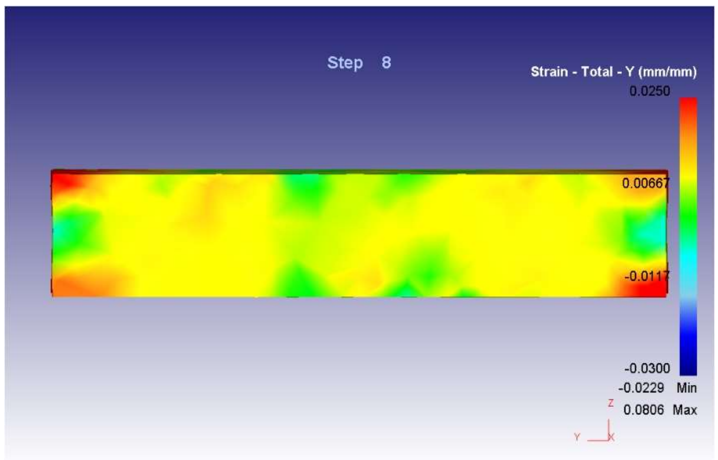
As an effect of reduction in thickness of the billet it undergoes elongation accompanied by lateral spread. Elongation on the billet can be observed through strain in X direction (fig. 10(b)). The positive strain in Y direction depicts the lateral spread of the material (fig. 10(c)) and the compression of the billet can be seen as a negative strain output in the Z direction (fig. 10(d)).



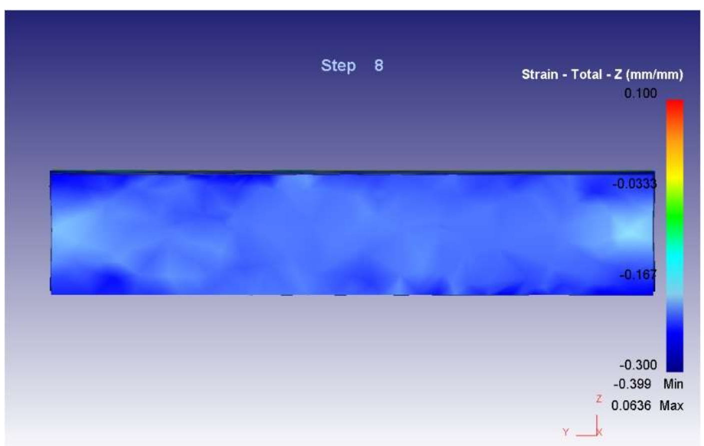
(a)



(b)



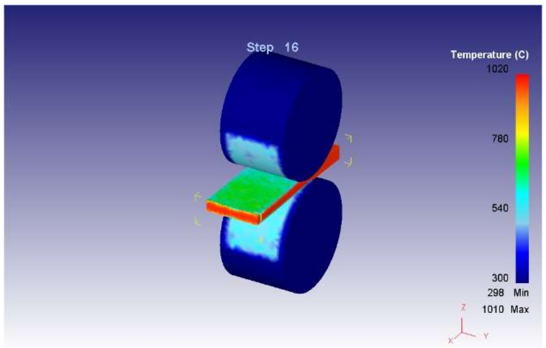
(c)



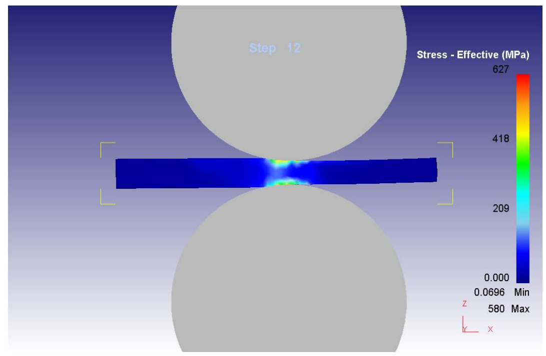
(d)

Figure 10: (a) Stress on the billet during cold rolling, (b) Strain in X direction, (c) Strain in Y direction, (d) Strain in Z direction

Similar kind of results were obtained for hot rolling of a flat billet with temperature of 1000 °C and pre-heated roller at 300 °C. Under hot rolling for a flat billet reduction was taken as 10% of initial thickness. As in hot rolling the billet temperature is reduced gradually, this allows the material to normalise its structure and become free of internal stress, maximum stress obtained was 627 MPa (fig. 11(b)).



(a)



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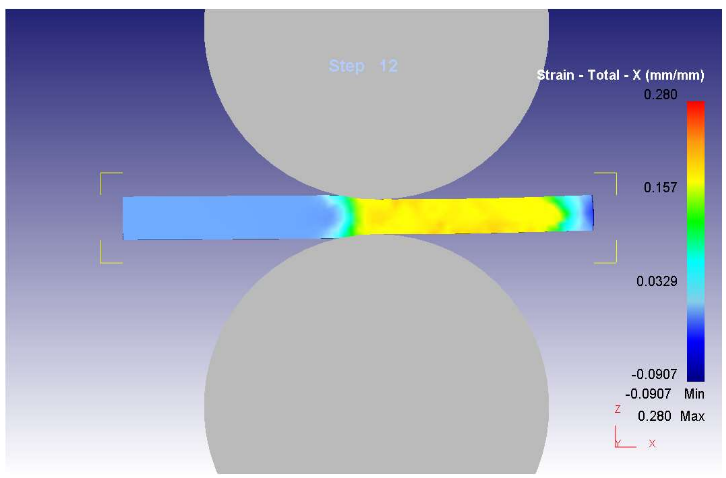
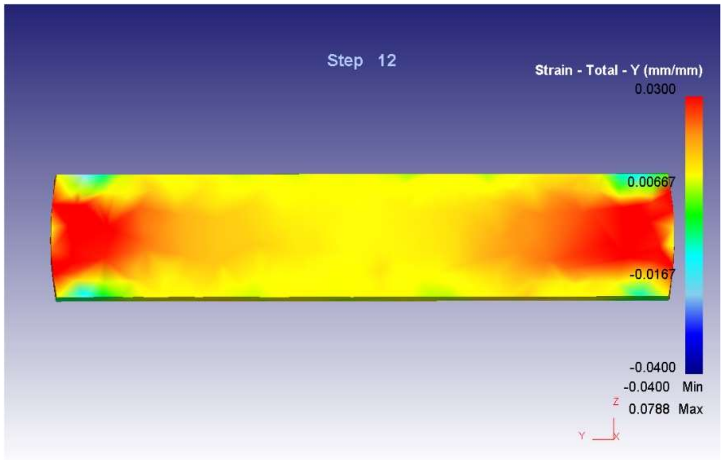


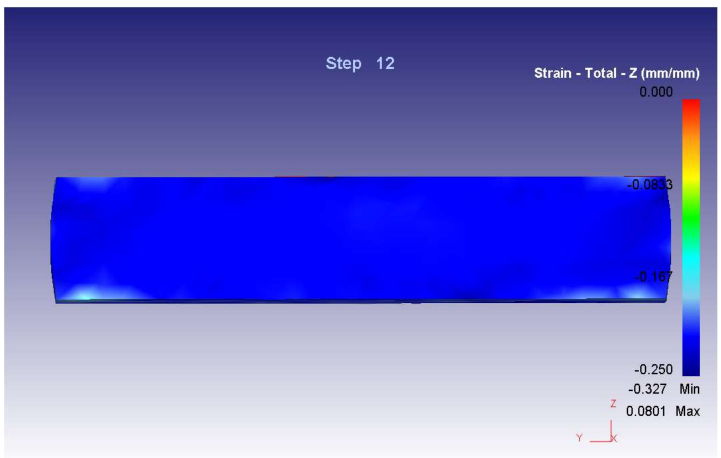
(c)

Figure 11: (a) Temperature variation over the billet for hot rolling, (b) Stress on the billet, (c) Strain in X direction

Increased temperature of the billet has allowed the metal to flow more freely compared to cold rolling. Hence the lateral spread is more in case of hot rolling. Bulge can be seen in fig. 12(a) at the middle of the cross section, where increases stress can be observed. Fig. 12 shows the contours of strain over the cross section in Y and Z direction.



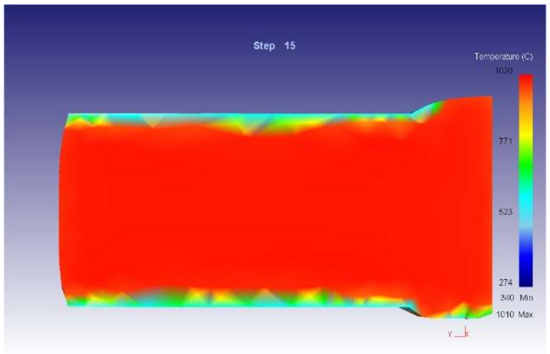
(a)



(b)

Figure 12: (a) Strain in Y direction, (b) Strain in Z direction

Based upon these, a 5-pass design was obtained for bulb bar and its post-processing was done. Initial contact was established at the neutral point of the billet and sn extra 6th pass was also added to reduce bending in the billet. The hot rolling simulation was done with pre-heated rollers at 400 °C and the billet at 1000 °C. The variation of temperature, strain and lateral velocity were obtained for study. Over the time period of operation temperature facilitates the metal flow and this can be used to generate varying cross section. Reduction being 20% for the billet the following contours are obtained for each pass.



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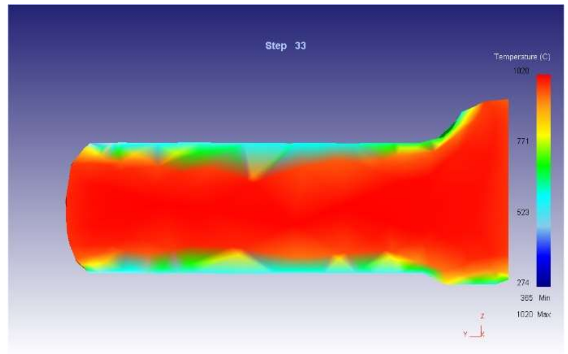

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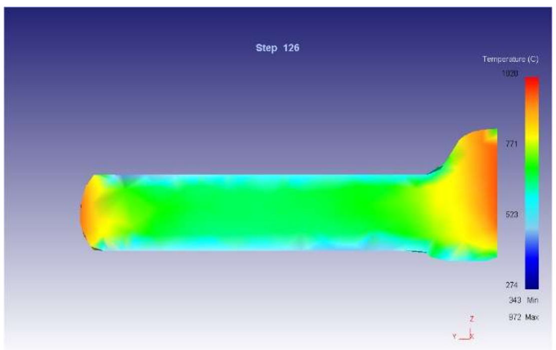

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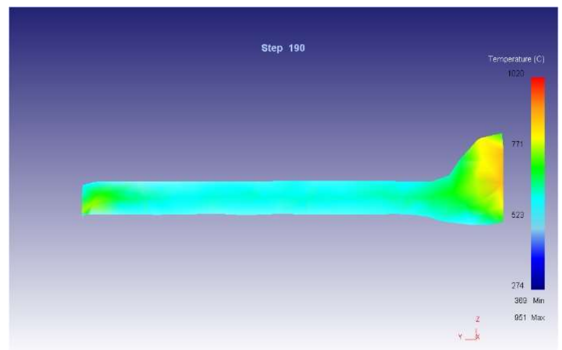

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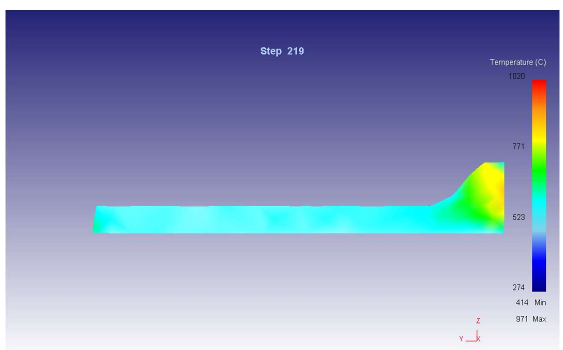

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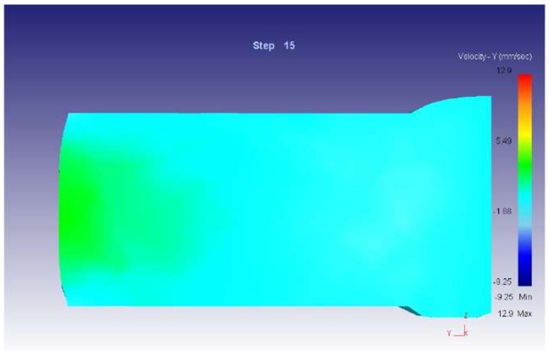
Figure 13: Variation of temperature over the cross section of the bulb bar



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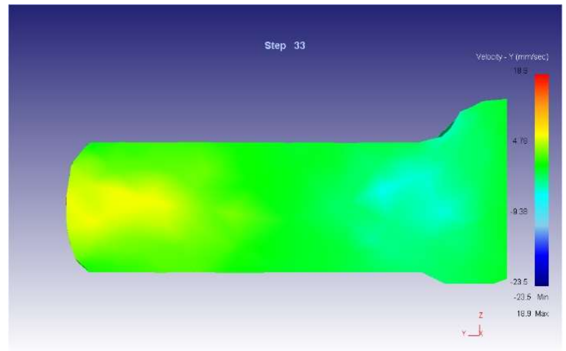

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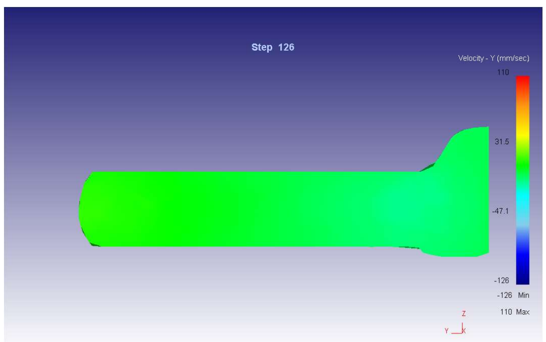

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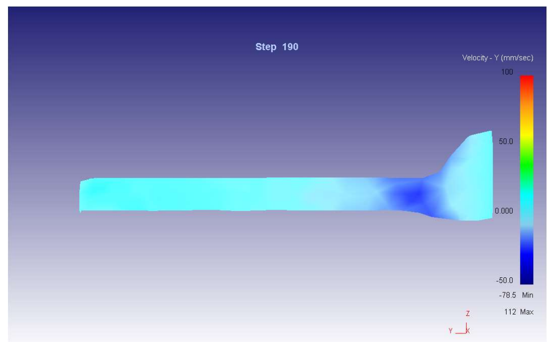

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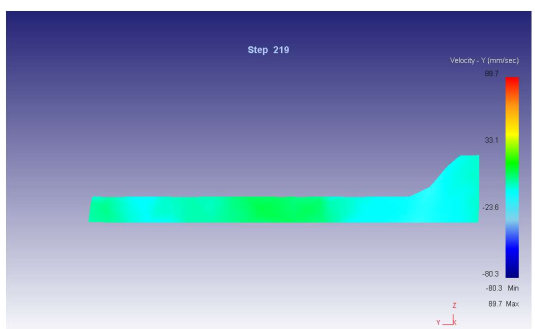

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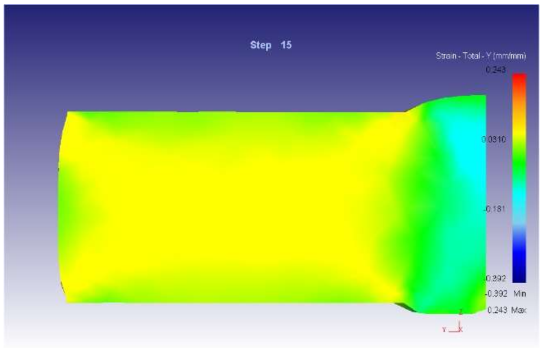
Figure 14: Variation of lateral velocity over the cross section of the bulb bar



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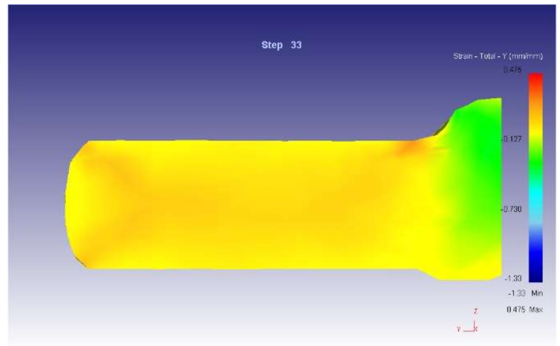

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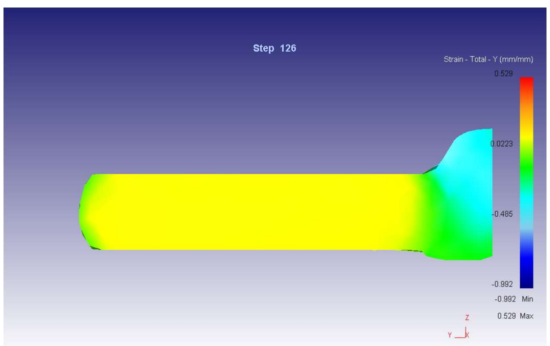

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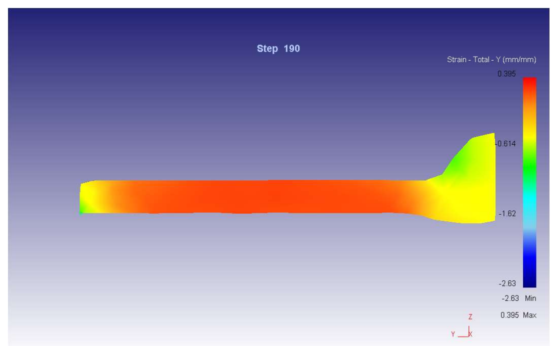

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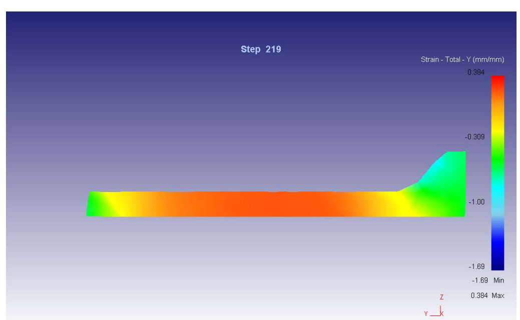

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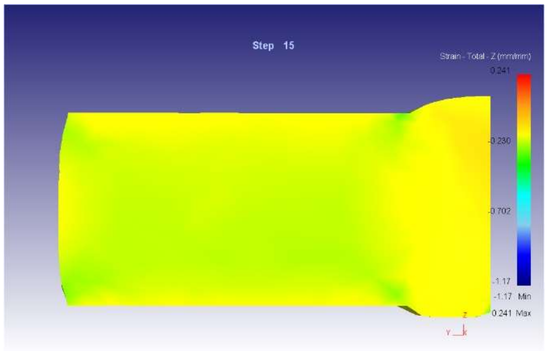
Figure 15: Variation of lateral strain (Y) over the cross section of the bulb bar



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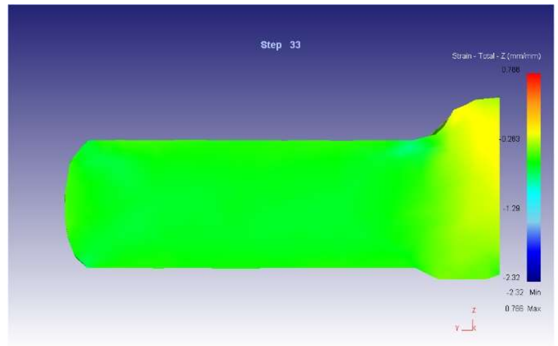

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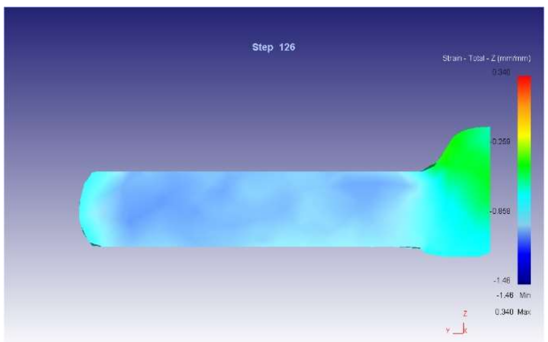
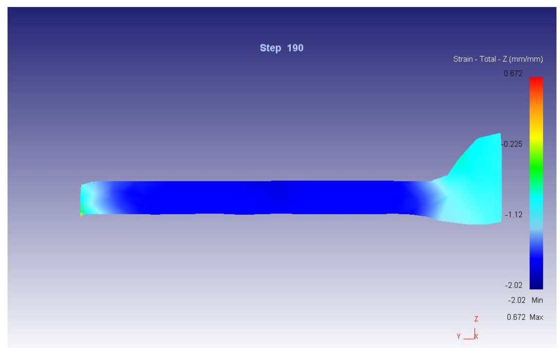
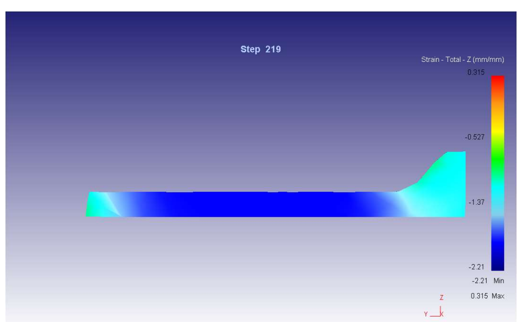


(c) Pass 3



(d) Pass 4



(e) Pass 5

Figure 16: Variation of stain in Z over the cross section of the bulb bar

As the billet is free to move in lateral direction its width increases gradually from initial 140mm to final 160 mm (fig. 17). For the final two passes a restriction is added so that the lateral dimensions are fixed.

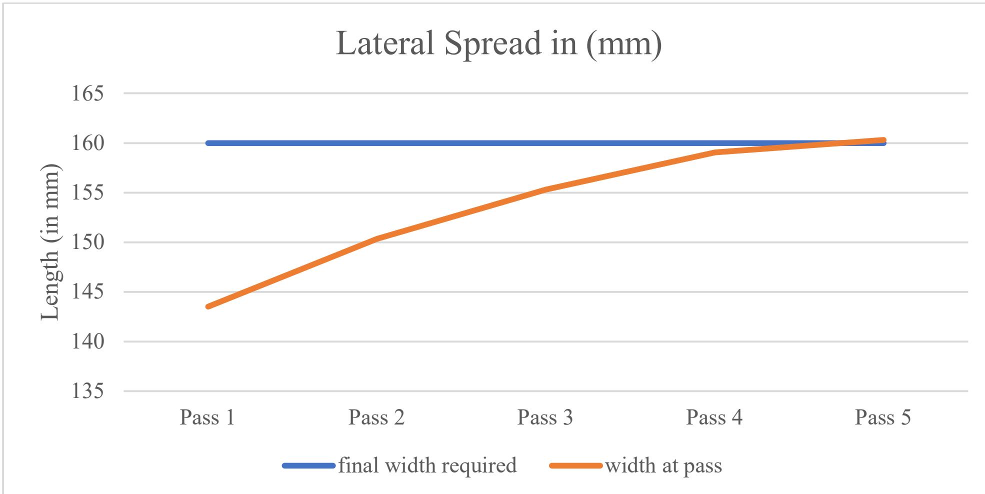


Figure 17: Width of the cross section at each pass

The contact area, with the roller, of the flat section of the bulb bar is more compared to the bulb section, it has a higher velocity than the later. This is observed as an increase in longitudinal strain at the flat section (table 2) and the flow of material is increased. The material in the bulb having less contact with the roller is drawn in forward direction, reducing the bulb height that should be obtained (fig. 18).

Table 2: Longitudinal strain (mm/mm) obtained at the two sections (approximate values)

Pass no.	Strain in flat section	Strain in bulb section
1	0.1838	0.179
2	0.4728	0.4738
3	0.8686	0.8684
4	1.485	1.458
5	1.657	1.634

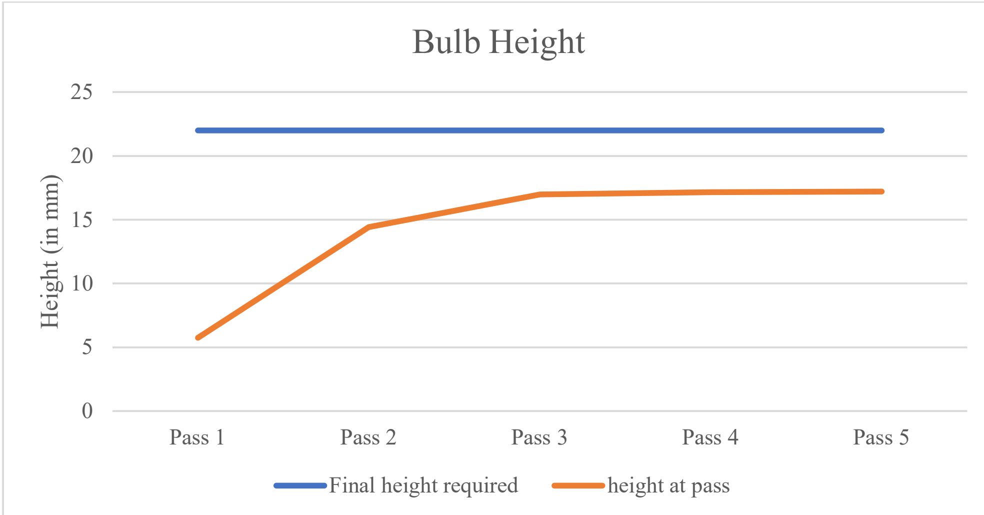


Figure 18: Increase in the bulb height

5. Conclusion

Hot rolling simulation was established in DEFORM 3D; a powerful process simulation system mainly used for metal forming processes based on finite element method (FEM). A combination of various factors obtained through number of simulations was used for the final roll pass design. Results obtained for the hot rolling of bulb bar showed the effect of temperature and draft on material flow and captured by the software with precision. The flow of material over the bulb section (strains and flow stress) and the bulb height obtained remains the main highlights.

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