FINITE ELEMENT MODELING AND ANALYSIS OF COLD RING ROLLING

A Thesis by

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FINITE ELEMENT MODELING AND ANALYSIS OF COLD RING ROLLING

I have examined the final copy of this thesis for form and content, and recommend that it be accepted in partial fulfillment of the requirement for the degree of Master of Science with a major in Mechanical Engineering.

Hamid Lankarani, Committee Chair

We have read this Thesis and recommend its acceptance:

Ramazan Asmatulu, Committee Member

Krishna Krishnan, Committee Member
DEDICATION

To my Parents
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ABSTRACT

Cold ring rolling is a complex metal forming process and generally not well understood. In many instances, considerable experience and experimentation is required to develop the process. During the process, plastic deformation behavior namely the plastic deformation state and its development in the deformation zone, has an important effect on the stability of the process. Hence, investigating the plastic deformation behavior in the deformation zone during the process is very significant for predicting the metal flow, controlling the quality of deformed rings and optimizing the process parameters. In this thesis, a study on plastic deformation behavior in cold ring rolling has been carried out through 2D numerical simulation using the LS-DYNA numerical finite element analysis code. The type of deformation behavior is compared with three type of plastic deformation behavior, established in previous studies. One type is that the material in the deformation zone entirely comes into the plastic deformation state at the early stage of the process (Type 1). A second type is that the material in the deformation zone gradually comes into the plastic deformation state during the process (Type 2). The last type is that at the end of process, there is still a rigid zone in elastic deformation or small plastic strain state near the middle radius of the ring blank (Type 3). The theoretical equations for decisive factor for plastic deformation behavior, which is the average amount of feed per revolution and functional relations between the average amount of feed per revolution and various process parameters, are ascertained with the assumption that the change in ring height during the process is negligible. Hence axial rolls are used to restrict the metal flow in axial direction of the ring. The simulation is performed for
another class of aluminum alloy and the results are explored. The simulation is performed by varying the decisive factors and the results are plotted for the effective plastic strain, vonmises stress and KE/IE ratio v/s time. The distribution of plastic strain through the thickness of the ring is also studied. A study on effect of the plastic deformation behavior on driver roll force was then carried out for both the materials. Through this thesis it was showed that it is required to run the cold ring rolling process at lower driver roll speed and higher feed rate. It is also required to have higher average amount of feed per revolution to achieve homogeneous deformation, uniform strain distribution and higher driver roll force. The results of this thesis in which a 2D FE analysis with plane strain formulation theory is carried out, can be used as a basis for optimizing the process parameters.
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## LIST OF ABBREVIATIONS

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<tr>
<td>PDB</td>
<td>Plastic Deformation Behavior</td>
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<td>FE</td>
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CHAPTER 1
INTRODUCTION

1.1 Definition of Rolling

Rolling is a process of plastically deforming metal by passing it between rolls. It is the most widely used forming process, which provides high production and close control of final product. The metal is subjected to very high compressive stresses as a result of the friction between the rolls and the metal surface.

1.2 Types of Rolling

Based on the temperature, the rolling is of 2 types:

- Hot rolling
- Cold rolling

1.2.1 Hot Rolling

It is a metallurgical process in which large metal sheets are deformed between roller at high temperature (usually above re-crystallization temperature) to form thinner cross sections. Hot rolling produces thinner cross sections than cold rolling processes with the same number of stages. Hot rolling will reduce the average grain size of a metal while maintaining an equi-axed microstructure.

A metal slab or billet is deformed between a set of work rolls maintained generally above its re-crystallization temperature. Hot rolling permits large deformations of the metal to be achieved with a low number of rolling cycles. As the rolling process breaks up the grains, they recrystallize maintaining an equi-axed structure and preventing the metal from hardening. Hot rolled material typically does not require annealing and the
high temperature will prevent residual stress from accumulating in the material resulting in better dimensional stability. Hot rolling is primarily concerned with manipulating material shape and geometry rather than mechanical properties. This is achieved by heating a component or material to its upper critical temperature and then applying controlled load which forms the material to a desired specification or size. Hot rolling is used mainly to produce sheet metal or simple cross sections such as railroad bars.

1.2.2 Cold Rolling

It is a metal working process in which, the metal is deformed by passing it through the rollers below its re-crystallization temperature. Cold rolling increases the yield strength and hardness of a metal by introducing defects into the metal's crystal structure. These defects prevent further slip and can reduce the grain size of the metal. Cold rolling is most often used to decrease the thickness of plate or sheet metal.

When a metal is cold worked, microscopic defects are nucleated throughout the deformed area. These defects can be either point defects (a vacancy on the crystal lattice) or a line defect (an extra half plane of atoms jammed in a crystal). As defects accumulate through deformation, it becomes increasingly more difficult for slip, or the movement of defects, to occur. This results in a hardening of the metal. If enough grains split apart, a grain may split into two or more grains in order to minimize the strain energy of the system. When large grains split into smaller grains, the alloy hardens as a result of the Hall-Petch relationship. If cold work is continued, the hardened metal may fracture. During cold rolling, metal absorbs a great deal of energy; some of this energy is used to nucleate and move defects (and subsequently deform the metal). The remainder of the energy is released as heat. While cold rolling increases the hardness and strength of
metal, it also results in a large decrease in ductility [3]. Thus metals strengthened by cold rolling are more sensitive to the presence of cracks and are prone to brittle fracture.

A metal that has been hardened by cold rolling can be softened by annealing. Annealing will relieve stresses, allow grain growth, and restore the original properties of the alloy. Ductility is also restored by annealing. Thus, after annealing, the metal may be further cold rolled without fracturing.

1.3 Cold Ring Rolling

Cold ring rolling is a highly efficient, low noise manufacturing process to produce high quality products and manufacture various precise seamless ring shape parts in industry related to aeronautics, bearings, automobile and rotating electrical machines. The inner roll (mandrel or pressure or idle roll) is idle and approaches the outer (main or driver or work roll) which is driven with a constant angular velocity and causes the ring to rotate. Decreasing the work piece thickness leads to an increase of the ring radius/height. Ring height is controlled in a closed pass radial rolling or by using a pair of identical guide rolls. Pair of guide rolls, which is usually controlled by a linkage mechanism, keeps the ring central and maintain circularity. Figure 1 shows the main components and typical deformation principle of ring rolling.

![Figure 1. Typical deformation principle diagram of ring rolling [1]](image-url)
1.4 Types of Ring Rolling

1.4.1 Radial Ring Rolling

In radial ring rolling, a round, pierced blank (doughnut) is placed over an inner roll (the mandrel). The wall thickness of the blank then is reduced between the mandrel and an outer contour roll by moving the two rolls in the radial direction, against each other while the blank is driven by the outer roll. The rolling force thus applied reduces the wall during each subsequent revolution, at the same time increasing the diameter.

1.4.2 Radial-Axial Ring Rolling

In radial-axial ring rolling, not only the wall thickness is decreased but also the height is reduced between a set of tapered rolls working on the ring in axial direction; both actions, of course causing the diameter to increase while the cross-section is reduced.

The major disadvantage of pure radial rolling mills is the requirement of special tools for each profile, since rings with clean faces, without hollowness, ridges or burrs can only be rolled in a pass which is closed, i.e. the sideways spread of material is restricted from the beginning of operation. Although rectangular cross section can be

Ring rolling is different from the standard rolling process in the fact that the ring rolling process is non-steady state throughout and a large number of ring rotations are required to finish the product. Although the finite element method might simulate this process accurately, it suffers from excessive computation time and convergence problems due to the highly nonlinear nature of the problem and the existence of complicated contact conditions. In order to reduce computational requirements several assumptions have been
employed, e.g., simulation in the vicinity of the roll gap [8-9], the ax symmetric forging approach method and plane strain simulations.

1.5 Plastic Deformation

When a sufficient load is applied to a metal or other structural material, it will cause the material to change shape. This change in shape is called deformation. When the stress is sufficient to permanently deform the metal, it is called plastic deformation. All shaping operations such as stamping, pressing, spinning, rolling, forging, drawing, and extruding involve plastic deformation of metals. Ductile materials undergo large plastic deformations than brittle materials. Plastic deformation may take place by:

- Slip
- Twinning

1.5.1 Deformation by Slip

When the yield stress is achieved one plane of atoms in crystal lattice glides over another. Few parallel slip planes form a block, neighboring with another block. Thus movement of the crystal planes is resulted in a series of steps, forming slip bands – black lines viewed under optical microscope.

1.5.2 Deformation by Twinning

Certain metals (Zn and Sn) deform by a process of twinning, differing from the normal slip mechanism, where all atoms in a block move the same distance. In the deformation by twinning atoms of each slip plane in a block move different distance, causing half of the crystal lattice to become a mirror image of another half.

Research and development of precise forming technology of cold ring rolling has become an important subject in advanced plastic processing fields. It is difficult to research the
plastic deformation behaviour in cold ring rolling by analytical and experimental methods due to complexity of the process, so a numerical simulation of the process will help in better understanding of the process and optimizing the process parameters.

It has been established in[1] that the, material in the deformation zone must entirely come into the plastic deformation state during the rolling process to cause the metal to flow in circumferential direction, resulting in expanding the diameter of the ring and gave a condition that the material in the deformation zone can entirely come into the plastic deformation state, i.e. the amount of feed per revolution (\(\Delta h\)) must exceed the minimum amount of feed (\(\Delta h_{\text{min}}\)) whose expression has been derived based on simplified deformation zone and slip line field method. Since the amount of feed per revolution changes with time the average amount of feed per revolution (\(\Delta h_{\text{Avg}}\)) is considered instead of \(\Delta h\).
CHAPTER 2
LITERATURE REVIEW

Cold ring rolling is an advanced but complex metal forming process under coupled effects with multi-factors, such as geometry sizes of rolls and ring blank, material, forming parameters, friction, etc. Numerous research institutes and industries have spent years working in determining the factors influencing cold ring rolling and trying to understand the pros and cons of cold ring rolling but the research is still limited. Certain useful results serving the base for further research in this field are discussed.

2.1 Fundamental Characteristics of Cold Ring Rolling Process [5]

The above study mainly concentrates on understanding the fundamental characteristics of the ring rolling process through finite element method. For this purpose steel ring with rectangular cross-sections are rolled on a mill with a driven mandrel and a work roll and was analyzed by 2-D elastic-plastic finite element method. The elastic constraint of the ring is neglected in order to save the computational time.

Figure 2. Finite element model (no guide rolls used) [5]
The analysis was performed using the finite element commercial code MARC K7.3 on the supercomputer NEC SX-4. In the analysis, the entire ring was analyzed for 3 revolutions as the pseudo-steady-state was attained and the fundamental characteristics of the whole process could be deduced. The deformation varied in first revolution as compared to other revolution. This is because during the first revolution the speed of the ring is almost same as the speed of the tools thus forming the slope of thickness along the circumference. As the ring moves to 2nd and subsequent revolutions the speed of the ring decreases and in turn increasing the reduction linearly.

Due to the bending effect of the ring as it passes through the second roll gap, the circumferential stress of the outer surface of the ring is compressive while those of the inner surface is tensile. The deformation characteristics can be estimated from several revolutions and the elastic constraint should not be neglected as the stress variations outside the roll bite are very large.

2.2 Effect of Sizes of Forming Rolls[6]

Cold ring rolling is a nonlinear and highly complex manufacturing process. It is said to be highly nonlinear under coupled effects of multifactor’s such as - sizes of forming rolls and ring blank, material, forming parameters, friction, etc. During the process, due to the change in size of forming roll a noticeable change can be seen in the value of amount of feed, the shape of the deformation and also in the dimension of the deformation, in turn having a significant effect on the metal flow and forming quality of the ring. The numerical calculation was carried under ABAQUS environment.
2.2.1 Average Spread $\bar{B}$

Considering the average spread of the deformed ring $\bar{B}$, it is given by [6]

$$\bar{B} = \frac{B_{\text{max}} - B_{\text{min}}}{2}$$

Where $B_{\text{max}}$ is the maximum spread and $B_{\text{min}}$ is the minimum spread in the ring.

The more the average spread $\bar{B}$ is, the more the metal of the ring blank flowing in axial direction. The average speed increases gradually then decreases with the increases of driver roll radius (Figure 2). When the driver roll radius increases to a larger value the metal flow in the axial direction decreases. This decrease is seen because of the decrease in average amount of feed per revolution. It is seen that with the increase of idle roll radius the average spread firstly decreases and then increases (Figure 3).

![Figure 3. Effect of size of forming roll on average spread [6]](image)

2.2.2 Fishtail Coefficient

The fish tail coefficient is defined as [6]
FT = \frac{B_{\text{max}} - B_{\text{min}}}{B_0} \quad \text{where } B_0 \text{ is the initial height of the ring blank}

The smaller the FT, the flatter is the end plane of the deformed ring, and the more homogeneous is the deformation in the axial direction of the deformed ring.

It is seen that first increases gradually, then decreases with the increase of the radius of driver roll (Figure 4). It can also be seen that the FT first decreases, and then increases with the increase of the radius of idle roll.

![Figure 4](image)

*Figure 4. Effect of size of forming roll on fishtail coefficient [6]*

2.2.3 Degree of Inhomogeneous Deformation of Deformed Ring

It can be defined as [6]

\[ \varphi_{sd} = \bar{\varepsilon}_{\text{max}} - \bar{\varepsilon}_{\text{min}} \]

Where,

- \( \varphi_{sd} \) is the degree of inhomogeneous deformation of deformed ring
- \( \bar{\varepsilon}_{\text{max}} \) is the maximum equivalent plastic strain of the deformed body
$\varepsilon_{\text{min}}$ is the minimum equivalent plastic strain of the deformed body

The more the degree of inhomogeneous deformation of deformed ring, leads to the danger of appearing material defects in the deformed ring.

It is seen that the degree of inhomogeneous deformation of deformed ring increases gradually with increase of driver roll radius (figure 5). It is also seen that the degree of inhomogeneous deformation of deformed ring firstly decrease and then increases with increase of idle roll radius.

![Figure 5. Effect of size of forming roll on Degree of inhomogeneous deformation of deformed ring [6](image)](image)

### 2.2.4 Force and Power Parameters

The effect of force and power parameters can be seen from the figure 6 & 7. It is seen that bigger the driver roll radius the smaller is the force leading to lesser power to produce plastic deformation. It is also seen that the bigger the radius of idle roll, bigger is the roll force resulting in bigger power producing a larger plastic deformation.
It is seen that the roll moment increases with the increasing driver roll radius and also can see that the radius of idle roll as a negligible effect on the roll moment.
2.3 Effect of Guide Roll

A new method called ‘thermal spokes’ has been proposed to simulate the effect of guide rolls. The method is successfully employed in a 2D FE simulation and its special feature is its ability to take into account the stiffness of the adjustment mechanism of the guide rolls and also a small change in the lever arm produces efficient change. Modeling and simulation effect of guide rolls is a very complex process which is because of the contact surfaces, the need to increase the mesh density at the contact area, and the unknown position and forces of the guide roll.

The thermal spokes method does not introduce nonlinearities to the model and has a minimal effect on computation cost. The main characteristics of thermal spokes method are (figure 8):

- A node is created in the center of the initial annular blank
- Elastic truss or spring elements are created to connect the central node to the modes on the mid layer of the ring. No bending or buckling effect is introduced due to the truss elements.
- Time dependent thermal body force is prescribed on the spokes in order to adjust the link length.
- Displacement boundary condition is prescribed to keep the central node on the symmetry plane of the mill and prevent the ring from tilting.

The main assumptions (figure 9) made under this method are

- The forces L1 and L2 are equal in magnitude and parallel
- Ideal contact conditions are assumed i.e., just one of the rolls touches the ring.
• An equal incoming length for the contact arc between the ring and both the main roll and mandrel is assumed, which makes it possible to calculate the contact length from geometry.

• Middle of the incoming outer and inner contact arcs are assumed to be the points of action of the forces L1 and L2 respectively.

The method does not introduce nonlinearities and frees the simulation from calculating the guide roll position. Guide roll arm stiffness can also be accounted. It has been seen that incorporating the guide rolls in the model affects the work piece-tool contact region, which in turn, affects the process parameters.

Figure 8. Thermal spokes model [7]
Figure 9. Thermal spokes method assumptions [7]

(a) Assumptions of Ref [4]

(b) New modifications

(c) Ideal condition for guide roll ring contact condition
2.4 Role of Friction\textsuperscript{[8]}

During the ring rolling process, the ring blank is continuously drawn into a gap between the rotating driver roll and a rotating idle roll, and since it produces continuous deformation of expansion in diameter and reduction in thickness under the action of friction and pressure from the rolls. So the friction between the rolls and ring plays an important role in keeping the stable forming of the process.

The influence of the friction on the cold ring rolling process is simulated under ABAQUS environment.

![Diagram](image)

**Figure 10.** 3D FE model with contact pairs (1) DRCS-RECS (2) IRCS-RICS (3) GRCS1-RECS (4) GRCS2-RECS \textsuperscript{[8]}

Six contacts surfaces have been defined including driver and idle rolls contact surfaces(DRCS and IRCS), ring exterior and interior contact surfaces (RECS and RICS) and guide rolls contact surfaces (GRCS1 and GRCS2), the four contact pairs have been defined, surfaces of which may contact one another as shown in figure 10. It is assumed
the frictions between the contact pairs meet the law of Coulomb and remains constant during the process. The effect of friction on cold ring rolling is explored by simulation under different friction coefficients between contact pairs of DRCS-RECS and IRCS-RICS, while the friction between the other 2 contact pairs remain zero.

![Image](image.png)

(a) $\mu=0.093$  (b) $\mu=0.103$  (c) $\mu=0.113$  (d) $\mu=0.123$

(a) $\mu=0.098$  (b) $\mu=0.088$  (c) $\mu=0.078$  (d) $\mu=0.068$

Figure 11. Deformed meshes under different friction coefficients [8]

The bigger the amount of thinning of ring blank, the greater the critical friction coefficient for stable forming of cold ring rolling under the same forming conditions. The results shows that the increasing friction coefficient is useful not only for improving the stability of cold ring rolling but also for improving the geometry and dimension precision of deformed ring.
2.5 Determining the main factors influencing plastic deformation behaviour in cold ring rolling.

During the cold ring rolling operation, continuous reduction in thickness of the ring blank does cause the metal of the ring blank to flow in circumferential directions of the ring thus leading to expansion in diameter. As average amount of feed per revolution \( \Delta h_{\text{Avg}} \) is adopted to describe the reducing behaviour of the thickness of the ring it is required to establish a relationship between \( \Delta h_{\text{Avg}} \) and other processing parameters. The bigger the \( \Delta h_{\text{Avg}} \), the more rapidly the thickness of the ring blank reduces, and more easily the material in the deformation zone comes into the plastic deformation state, and vice versa. So the reducing behaviour of the thickness of the ring is just a decisive factor in the plastic deformation behaviour and plays a decisive role in metal flow.

Firstly, the roll time [1]

\[
T = \frac{\Delta H}{\gamma}
\]

(1)

Where,

\( \Delta H \) = Change in thickness of the ring in mm, which is given by \( \Delta H = H_o - H_f \).

\( H_o \) = Initial thickness of the ring blank in mm.

\( H_f \) = Final thickness of the ring blank in mm.

\( \gamma \) = Feed rate in mm/sec.

Secondly, assuming the volume constancy and the spread of ring blank in axial direction as negligibly small (Plane strain condition), we have [1]

\[
\pi(R_o^2 - r_i^2) = \pi(R_i^2 - r_o^2), \quad \text{and} \quad r_i = R_i - H_i
\]
\[ R_i = \frac{1}{2} \left[ \left( R_o + r_o \right) \frac{H_o}{H_i} + H_i \right], \quad (i = 1, 2, 3\ldots n), \quad (2) \]

Where

\( R_i \) and \( r_i = i^{th} \) revolution instantaneous outer and inner radius of the ring blank in mm.

\( R_o \) and \( r_o \) = Initial outer and inner radius of the ring blank in mm.

\( H_o \) = Initial thickness of the ring blank in mm.

\( H_i \) = Thickness of the ring blank at the end of \( i^{th} \) revolution in mm.

\( n \) = Total number of rotations required to complete one whole operation.

Third, assuming no sliding between driver roll and ring blank, the distance covered by driver roll is equal to the circumference of the ring blank at that instant,

\[ \Delta t = \frac{2\pi R_i}{n_1 \pi}, \quad \therefore \Delta t = \frac{R_i}{n_1}, \]

\[ t_i = \sum_{j=1}^{n} \Delta t_j, \quad (i = 1, 2, 3\ldots n), \quad (3) \]

Where

\( \Delta t_i \) = Time needed during the \( i^{th} \) revolution in Secs.

\( R_i \) = Radius of the driver roll in mm.

\( n_1 \) = Driver roll rotational speed in rpm.

Then we have the feed for the \( i^{th} \) revolution as

\[ H_{i-1} - H_i = \gamma \Delta t_i = \frac{\gamma R_i}{R_i n_1}, \quad (i = 1, 2, 3\ldots n), \quad (4) \]

Where

\( H_{i-1} \) = Thickness of the ring blank at the end of \( (i-1)^{th} \) revolution in mm.
Third, from (2) and (3), the $i^{th}$ revolution instantaneous thickness $H_i$ of the ring is obtained,

$$H_i = \frac{H_{i-1} + \sqrt{H_{i-1}^2 - 4(a+1)ab}}{2(a+1)} , \quad (i = 1, 2, 3,...n),$$ (5)

Where

$$a = \frac{30\gamma}{R_1n_1}$$

$$b = (R_o + r_o)H_o$$

So from equation (5) it is clear that the $i^{th}$ revolution instantaneous thickness $H_i$ is a function of $\gamma$, $R_1$, $n_1$ and initial dimensions of the ring.

Lastly, the amount of feed per revolution $\Delta h_i$ is given by

$$\Delta h_i = H_{i-1} - H_i , \quad (i = 1, 2, 3,...n),$$ (6)

Since the amount of feed per revolution is time dependent and will be changing constantly with time, the average amount of feed per revolution $\Delta h_{Avg}$ is used in place of $\Delta h$, which is given by

$$\Delta h_{Avg} = \frac{\sum_{i=1}^{n} \Delta h_i}{n} ,$$ (7)

From equation (6) and (7) it is clear that the decisive factor in plastic deformation behaviour i.e. $\Delta h_{Avg}$ is in turn dependent on radius of driver roll $R_1$, rotational speed of driver roll $n_1$, feed rate $\gamma$ and initial dimensions of the ring blank. In this study only the effect of driver roll speed and feed rate are considered.

The value of $\Delta h_{Avg}$ calculated using the equation (7) should satisfy the following condition for successful ring rolling process, which is given by [1],

$$[\text{condition}]$$
\[ \Delta h_{\text{min}} \leq \Delta h_{\text{avg}} \leq \Delta h_{\text{max}}, \]  

(8)

Where

\[ \Delta h_{\text{min}} \] is the minimum amount of feed by which the material in the deformation zone can entirely come into plastic deformation state, and \( \Delta h_{\text{max}} \) is the maximum amount of feed allowed to make the ring blank be nipped into the roll gap continuously, the expressions of which are derived based on simplified deformation zone and slip line field method\(^1\).

\[ \Delta h_{\text{min}} = 6.55 \times 10^{-3} (R - r)^2 \left( \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R} - \frac{1}{r} \right), \]  

(9)

\[ \Delta h_{\text{max}} = \beta^2 \left[ \frac{2R_1}{(1 + R_1/R_2)^2} \left( 1 + \frac{R_1}{R_2} + \frac{R_1}{R} - \frac{R_1}{r} \right) \right], \]  

(10)

Where

R and \( r \) = Instantaneous outer and inner radius off the ring in mm.

\( R_1 \) = Driver roll radius in mm.

\( R_2 \) = Idle roll radius in mm.

\( \beta \) = Friction angle, which is given by\(^1\) \( \beta = \tan^{-1} \mu \).

Since \( \Delta h_{\text{min}} \) and \( \Delta h_{\text{max}} \) will be changing with time they are discretized as \( \Delta h_{\text{min},i} \) and \( \Delta h_{\text{max},i} \) at each revolution and \( R \) and \( r \) are replaced by \( R_i \) and \( r_i \) to obtain a set of values for \( \Delta h_{\text{min}} \) and \( \Delta h_{\text{max}} \), then the equation (8) is written in more generalized form as

\[ (\Delta h_{\text{min},i})_{\text{max}} \leq \Delta h_{\text{avg}} \leq (\Delta h_{\text{max},i})_{\text{min}}, \]  

(11)

Where

\( (\Delta h_{\text{min},i})_{\text{max}} \) is the maximum of \( \Delta h_{\text{min},i} \) and \( (\Delta h_{\text{max},i})_{\text{min}} \) is the minimum of the \( \Delta h_{\text{max},i} \).
CHAPTER 3
FINITE ELEMENT MODEL

3.1. Components of Cold Ring Roll

The main components of cold ring roll are:

- Driver Roll
- Idle Roll
- Ring Blank
- Guide Roll
- Spring Element

Each of the above components is discussed in detail in the following sub-sections.

3.1.1 Driver Roll

It is also called as the main roll. It is a driving roll which rotates in a fixed position. The speed of the roll can be varied. It remains in contact with the ring blank throughout the ring rolling process. The driver roll is a rigid part. The dimensions used in modeling of driver roll are given in Table 1. The figure 12 shows the driver roll and its axis of rotation. It has only Z- rotational degree of freedom

![Figure 12. Driver Roll](image-url)
3.1.2 Idle Roll

It is also called as mandrel. It main purpose is to load the ring blank during the process and unload the deformed ring when the process is finished. It is a rigid part and the most important components in cold ring roll. It remains in the contact with ring blank throughout the process and ensures that the ring blank is in contact with the driver roll during the process. It controls the guide roll through the spring element. The dimensions used in modeling of idle roll are given in Table 1. The figure 13 shows the driver roll and its axis of rotation. It rotates opposite to the direction of the driver roll. It has Z-rotational along with Y- displacement degree of freedom.

![Figure 13. Idle Roll](image)

3.1.3 Ring Blank

It is the raw product used in the cold ring rolling process. It is the only deformable component. The ring blank remains in contact with all the other components of the cold ring roll. In 3D model used in industries, the type of contact formed between the ring blank and the driver roll is a line contact, whereas as in this thesis since we have assumed a plane strain formulation the type of contact formed is point contact. The ring blank is made to rotate in the gap formed by the driver and the idle roll. The rotation and the
displacement of the ring blank is controlled by the idle roll. The dimensions used in modeling of idle roll are given in Table 1. The figure 14 shows the ring blank and its axis of rotation. Its rotation is same as the idle roll. It has Z-rotational along with Y-displacement degree of freedom.

![Figure 14. Initial and deformed ring blank](image)

3.1.4 Guide Roll

It is also called as centering roll. Its main purpose is to ensure that it restricts the ring blank from moving away of its rotating axis, so that the ring can retain its original circular shape. Its position is controlled by the spring element which connects the guide roll with the idle roll. It is a rigid part. In industries, the guide rolls are controlled using pneumatic drives, but since it is not possible to simulate pneumatic drives in 2D element formulation 1D spring elements are used. The guide rolls are two in number which remains in contact with the outer surface of the ring blank. It also needs to ensure that the force exerted by the guide rolls does not cause any kinds of damage to the ring blank. The dimensions used in modeling of guide roll are given in Table 1. The figure 15 shows the
guide rolls and its axis of rotation. It has Z-rotational along with X-displacement degree of freedom.

![Figure 15. Guide Roll](image)

3.1.5 Spring Element

It is 1D discrete spring element. It connects and controls the guide rolls with the idle roll. Spring elements are two in number in order to connect two guide rolls. In industries, the guide rolls are controlled using pneumatic drives, but since it is not possible to simulate pneumatic drives in 2D element formulation 1D spring elements are used. It is usually defined by its stiffness. The figure 16 shows the 1D spring element.

![Figure 16. 1D spring Element](image)

3.2. Full FE Model Description

The full FE model is as shown in figure 17. A 2-Dimensional finite element model was developed using Pro/E and Hypermesh as Pre-processor. The dimensions used in modeling the FE model are given in Table 1.
Table 1

Dimensions used in finite element modeling

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value in mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer radius of ring blank</td>
<td>$R_o$</td>
</tr>
<tr>
<td>Inner radius of ring blank</td>
<td>$r_o$</td>
</tr>
<tr>
<td>Height of ring blank</td>
<td>$B_o$</td>
</tr>
<tr>
<td>Thickness of ring blank</td>
<td>$H_o$</td>
</tr>
<tr>
<td>Radius of driver roll</td>
<td>$R_1$</td>
</tr>
<tr>
<td>Radius of Idle roll</td>
<td>$R_2$</td>
</tr>
<tr>
<td>Radius of guide roll</td>
<td>$R_3$</td>
</tr>
</tbody>
</table>

![2-dimensional model showing all the components](image)

Figure 17. 2-dimensional model showing all the components
Under LS-DYNA environment, a 2 dimensional finite element model was developed for simulation of cold ring rolling as shown in the figure 17. The explicit dynamic procedure is used to avoid the huge computation time and the convergence problem of the implicit procedure.

- 4 nodded 2-D shell elements with plane strain formulation theory are used
- Ring blank – Iso mesh
- All rigid bodies – Paver mesh
- Number of integration points – 1
- Analysis is carried out without adaptive remeshing.

### 3.3 Material

#### Table 2

a. Material properties of Aluminum alloy

<table>
<thead>
<tr>
<th>Material property</th>
<th>Aluminum Alloy HE30</th>
<th>Aluminum Alloy 6061-O</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SI units</td>
<td>Used values in consistent with model units</td>
</tr>
<tr>
<td>Density</td>
<td>2700 Kg/m³</td>
<td>2.7e-06 Kg/mm³</td>
</tr>
<tr>
<td>Young's modulus</td>
<td>74e+09 N/m²</td>
<td>74e+06 Kg/mm²·Sec²</td>
</tr>
<tr>
<td>Yield strength</td>
<td>231.6e+06 N/m²</td>
<td>231.6e+03 Kg/mm²·Sec²</td>
</tr>
<tr>
<td>Poisson's ratio</td>
<td>0.33</td>
<td>0.33</td>
</tr>
</tbody>
</table>
Table 2

b. Material properties of Steel

<table>
<thead>
<tr>
<th>Material property</th>
<th>SI units</th>
<th>Used values in consistent with model units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>7850 Kg/m³</td>
<td>7.85e-06 Kg/mm³</td>
</tr>
<tr>
<td>Young's modulus</td>
<td>210e+09 N/m²</td>
<td>210e+06 Kg/mm-Sec²</td>
</tr>
<tr>
<td>Poisson's ratio</td>
<td>0.28</td>
<td>0.28</td>
</tr>
</tbody>
</table>

3.3.1 Material Model of Ring Blank

The material properties used in modeling the ring blank are as shown in Table 2. The material used is an elastic–plastic aluminum alloy HE30 with the constitutive equation,

\[ \sigma_{\text{eff}} = 69000 \times \varepsilon_{\text{eff}}, \quad \text{MPa} \quad \text{for} \quad \varepsilon_{\text{eff}} \leq 0.003, \]

\[ \sigma_{\text{eff}} = 231.6 \left(1 + 3001.8 \varepsilon_{\text{eff}}\right)^{0.0653}, \quad \text{MPa} \quad \text{for} \quad \varepsilon_{\text{eff}} > 0.003, \quad \text{Where} \]

\[ \sigma_{\text{eff}} = \text{True stress}, \]

\[ \varepsilon_{\text{eff}} = \text{Total true strain}. \]

Material model

* MAT_PIECEWISE_LINEAR_PLASTICITY

** MID RO E PR SIGY **

1 2.7E-06 74E+06 0.33 231.6E+03

C P LCSS

3
The FE analysis was repeated using aluminum alloy 6061-O. The material model and the constitutive equation,

$$\sigma_{eff} = 55.2 \left(1 + 845.03 \varepsilon_{eff} \right)^{0.2} \text{ MPa}$$

Material model

* MAT_PIECEWISE_LINEAR_PLASTICITY

<table>
<thead>
<tr>
<th>MID</th>
<th>RO</th>
<th>E</th>
<th>PR</th>
<th>SIGY</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.7E-06</td>
<td>68.9E+06</td>
<td>0.33</td>
<td>55.2E+03</td>
</tr>
</tbody>
</table>

C    P    LCSS

3

A curve has been defined for the true stress and strain variation using the above mentioned constitutive equation of both the materials (figure 18).

![True Stress v/s True Strain](image)

Figure 18. The variation curve of True stress v/s True strain
3.3.2 Material Model of Driver Roll, Idle Roll and Guide Roll

The material used is steel and its properties are as shown in Table 2.

Material model

* MAT_RIGID

<table>
<thead>
<tr>
<th>MID</th>
<th>RO</th>
<th>E</th>
<th>PR</th>
</tr>
</thead>
<tbody>
<tr>
<td>@</td>
<td>7.85E-06</td>
<td>2.1E+08</td>
<td>0.28</td>
</tr>
</tbody>
</table>

CMO CON1 CON2

-1 @ @

Different material cards are used for driver roll, idle roll and guide rolls as the displacement constraints are applied with respect to the local co-ordinate systems which are defined at their respective centers. (@ Refer LSDYNA Manual for the values)

3.3.3 Material model of One-Dimensional spring element

Material model

* MAT_SPRING_ELASTIC

<table>
<thead>
<tr>
<th>MID</th>
<th>K</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>50000</td>
</tr>
</tbody>
</table>

It is assumed that the friction on the contact surfaces between the roll and the ring blank meets the law of Coulomb and remains unchanged during the process.

- Coulomb friction Co-efficient at contact interface of ring, driver roll and idle roll is taken as 0.2.
- Coulomb friction Co-efficient at contact interface of ring and guide rolls is taken as 0.

Linear displacement curve is used in the analysis for giving feed i.e. to describe the
motion of idle roll in Y-direction which results in thickness reduction of the ring blank. Figure 19 shows the linear displacement curve used in defining the idle roll movement for different cases of cold ring rolling process.

![Feed V/S Time for different cases of loading](image)

Figure 19. The Displacement curve used to define idle roll movement.

### 3.4. Contact between the components

The contact plays an important role in the FE simulation. In this thesis, since we have used 2D element formulation all the contact between the driver roll, ring blank, idle roll and guide rolls are defined using the following type of contact. Since we have point contacts the static and dynamic friction are taken as 0.2 for driver roll –ring blank and idle roll- ring blank contacts. The other contact between the ring blank and guide rolls are taken as zero.

```plaintext
*CONTACT_2D_AUTOMATIC_SURFACE_TO_SURFACE_ID

cid 1

Sids sidm sfact freq fs fd dc membs
# # 0 0 0.2 0.2
```

(# refer appendix)
CHAPTER 4
CALCULATIONS OF AVERAGE AMOUNT OF FEED PER REVOLUTION

The calculations are carried out based on the theoretical model developed in the previous chapter. If a group of initial dimensions of the ring blank are selected, then the average amount of feed per revolution depends upon driver roll rotational speed ($n_1$) and feed rate ($\gamma$), therefore two cases are considered where $n_1$ is varied in one and $\gamma$ in the second case. The results of the first case are compared with the previous literature for understanding the plastic deformation behaviour and the FE Modelling is evaluated, the results of the second case are studied for understanding the plastic deformation behaviour and its effect on driver roll force.

4.1 CASE 1 – Driver Roll Speed is varied with Feed Rate Constant at 1.22mm/sec for Material HE30

The average amount of feed per revolution for each case is calculated by varying the driver roll speed and the feed rate is kept constant at 1.22 mm/sec

Reduction in thickness is taken as 28% i.e. ring is reduced to a final thickness of 16.0056mm from initial thickness of 22.23mm.

Process time,

$$T = \frac{\Delta H}{\gamma} = \frac{6.224}{1.22} = 5.1 \text{ Secs}$$

Average amount of feed per revolution for model dimensions as per Table 1. The process time remains the same for all sub-cases of Case1. The instantaneous values after each revolution of the ring of different parameters are tabulated.
4.1.1 CASE 1a – Driver Roll Speed of 60 rpm

Driver roll speed \( n_1 = 60 \text{ rpm} \), :. \( a = 0.0058 \) and \( b = 2258.56 \)

Table 3

Instantaneous values after each revolution of ring \( (n_1 = 60 \text{ rpm}) \)

<table>
<thead>
<tr>
<th>i</th>
<th>( r_i )</th>
<th>( r_i' )</th>
<th>( \Delta h_{\text{min}} )</th>
<th>( \Delta h_{\text{max}} )</th>
<th>( \Delta t_i )</th>
<th>( \Delta h_i )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>61.915</td>
<td>39.685</td>
<td>0.094</td>
<td>1.562</td>
<td>0.591</td>
<td>0.721</td>
</tr>
<tr>
<td>1</td>
<td>63.288</td>
<td>40.048</td>
<td>0.094</td>
<td>1.571</td>
<td>0.593</td>
<td>0.723</td>
</tr>
<tr>
<td>2</td>
<td>64.822</td>
<td>40.413</td>
<td>0.093</td>
<td>1.580</td>
<td>0.595</td>
<td>0.726</td>
</tr>
<tr>
<td>3</td>
<td>66.548</td>
<td>40.779</td>
<td>0.093</td>
<td>1.588</td>
<td>0.598</td>
<td>0.729</td>
</tr>
<tr>
<td>4</td>
<td>68.503</td>
<td>41.147</td>
<td>0.092</td>
<td>1.597</td>
<td>0.600</td>
<td>0.732</td>
</tr>
<tr>
<td>5</td>
<td>70.736</td>
<td>41.516</td>
<td>0.091</td>
<td>1.605</td>
<td>0.602</td>
<td>0.735</td>
</tr>
<tr>
<td>6</td>
<td>73.314</td>
<td>41.887</td>
<td>0.091</td>
<td>1.613</td>
<td>0.604</td>
<td>0.737</td>
</tr>
<tr>
<td>7</td>
<td>76.325</td>
<td>42.259</td>
<td>0.090</td>
<td>1.621</td>
<td>0.607</td>
<td>0.740</td>
</tr>
<tr>
<td>8</td>
<td>79.898</td>
<td>42.632</td>
<td>0.090</td>
<td>1.629</td>
<td>0.609</td>
<td>0.743</td>
</tr>
<tr>
<td>9</td>
<td>84.217</td>
<td>43.007</td>
<td>0.089</td>
<td>1.637</td>
<td>0.612</td>
<td>0.746</td>
</tr>
<tr>
<td>10</td>
<td>89.568</td>
<td>43.384</td>
<td>0.088</td>
<td>1.644</td>
<td>0.614</td>
<td>0.749</td>
</tr>
</tbody>
</table>

Maximum of \( \Delta h_{\text{min}} = 0.094 \)

Minimum of \( \Delta h_{\text{max}} = 1.562 \)

\( \Delta h_{\text{Avg}} = 0.808 \)

Since \( \Delta h_{\text{Avg}} \) is large value, Type.1 deformation behaviour is expected as the thickness of the ring reduces rapidly, i.e. the material in the deformation zone comes into the plastic state more easily.
4.1.2 CASE 1b – Driver Roll Speed of 160 rpm

Driver roll speed $n_1 = 160$ rpm, $\therefore a = 0.00218$ and $b = 2258.56$

Table 5

Instantaneous values after each revolution of ring ($n_1 = 160$ rpm)

<table>
<thead>
<tr>
<th>i</th>
<th>$R_i$</th>
<th>$r_i$</th>
<th>$\Delta h_{\text{min}}$</th>
<th>$\Delta h_{\text{max}}$</th>
<th>$\Delta t$</th>
<th>$\Delta h_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>61.915</td>
<td>39.685</td>
<td>0.094</td>
<td>1.598</td>
<td>0.222</td>
<td>0.27</td>
</tr>
<tr>
<td>1</td>
<td>62.002</td>
<td>39.821</td>
<td>0.093</td>
<td>1.618</td>
<td>0.223</td>
<td>0.272</td>
</tr>
<tr>
<td>2</td>
<td>62.09</td>
<td>39.958</td>
<td>0.092</td>
<td>1.636</td>
<td>0.225</td>
<td>0.275</td>
</tr>
<tr>
<td>3</td>
<td>62.178</td>
<td>40.095</td>
<td>0.091</td>
<td>1.655</td>
<td>0.227</td>
<td>0.277</td>
</tr>
<tr>
<td>4</td>
<td>62.267</td>
<td>40.232</td>
<td>0.089</td>
<td>1.673</td>
<td>0.229</td>
<td>0.279</td>
</tr>
<tr>
<td>5</td>
<td>62.355</td>
<td>40.369</td>
<td>0.088</td>
<td>1.69</td>
<td>0.231</td>
<td>0.282</td>
</tr>
<tr>
<td>6</td>
<td>62.444</td>
<td>40.506</td>
<td>0.086</td>
<td>1.707</td>
<td>0.233</td>
<td>0.285</td>
</tr>
<tr>
<td>7</td>
<td>62.534</td>
<td>40.644</td>
<td>0.085</td>
<td>1.724</td>
<td>0.236</td>
<td>0.287</td>
</tr>
<tr>
<td>8</td>
<td>62.623</td>
<td>40.781</td>
<td>0.083</td>
<td>1.74</td>
<td>0.238</td>
<td>0.29</td>
</tr>
<tr>
<td>9</td>
<td>62.713</td>
<td>40.919</td>
<td>0.081</td>
<td>1.756</td>
<td>0.24</td>
<td>0.293</td>
</tr>
<tr>
<td>10</td>
<td>62.804</td>
<td>41.057</td>
<td>0.08</td>
<td>1.772</td>
<td>0.243</td>
<td>0.297</td>
</tr>
</tbody>
</table>

Maximum of $\Delta h_{\text{min}} = 0.094$

Minimum of $\Delta h_{\text{max}} = 1.598$

$\Delta h_{\text{Avg}} = 0.311$

Since $\Delta h_{\text{Avg}}$ is large value Type.1 deformation behavior is expected as the thickness of the ring reduces rapidly, i.e. the material in the deformation zone comes into the plastic state more easily.
4.1.3 CASE 1c – Driver Roll Speed of 350 rpm

Driver roll speed \( n_1 = 350 \text{ rpm} \), \( a = 0.0010 \) and \( b = 2258.56 \)

Table 6

Instantaneous values after each revolution of ring \((n_1 = 350 \text{ rpm})\)

<table>
<thead>
<tr>
<th>( i )</th>
<th>( R_i )</th>
<th>( r_i )</th>
<th>( \Delta h_{\text{min}} )</th>
<th>( \Delta h_{\text{max}} )</th>
<th>( \Delta t_i )</th>
<th>( \Delta h_i )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>61.915</td>
<td>39.685</td>
<td>0.094</td>
<td>1.562</td>
<td>0.101</td>
<td>0.124</td>
</tr>
<tr>
<td>1</td>
<td>61.955</td>
<td>39.747</td>
<td>0.094</td>
<td>1.563</td>
<td>0.101</td>
<td>0.124</td>
</tr>
<tr>
<td>2</td>
<td>61.995</td>
<td>39.810</td>
<td>0.094</td>
<td>1.565</td>
<td>0.101</td>
<td>0.124</td>
</tr>
<tr>
<td>3</td>
<td>62.035</td>
<td>39.872</td>
<td>0.094</td>
<td>1.567</td>
<td>0.101</td>
<td>0.124</td>
</tr>
<tr>
<td>4</td>
<td>62.075</td>
<td>39.935</td>
<td>0.094</td>
<td>1.568</td>
<td>0.102</td>
<td>0.124</td>
</tr>
<tr>
<td>5</td>
<td>62.116</td>
<td>39.997</td>
<td>0.094</td>
<td>1.570</td>
<td>0.102</td>
<td>0.124</td>
</tr>
<tr>
<td>6</td>
<td>62.156</td>
<td>40.060</td>
<td>0.094</td>
<td>1.571</td>
<td>0.102</td>
<td>0.124</td>
</tr>
<tr>
<td>7</td>
<td>62.196</td>
<td>40.122</td>
<td>0.094</td>
<td>1.573</td>
<td>0.102</td>
<td>0.124</td>
</tr>
<tr>
<td>8</td>
<td>62.237</td>
<td>40.185</td>
<td>0.094</td>
<td>1.574</td>
<td>0.102</td>
<td>0.124</td>
</tr>
<tr>
<td>9</td>
<td>62.277</td>
<td>40.248</td>
<td>0.093</td>
<td>1.576</td>
<td>0.102</td>
<td>0.124</td>
</tr>
<tr>
<td>10</td>
<td>62.318</td>
<td>40.310</td>
<td>0.093</td>
<td>1.577</td>
<td>0.102</td>
<td>0.124</td>
</tr>
</tbody>
</table>

Maximum of \( \Delta h_{\text{min}} = 0.094 \)

Minimum of \( \Delta h_{\text{max}} = 1.562 \)

\( \Delta h_{\text{Avg}} = 0.136 \)

Since \( \Delta h_{\text{Avg}} \) is small value Type.2 deformation behaviour is expected as the thickness of the ring reduces gradually, i.e. the material in the deformation zone gradually comes into the plastic state during the cold ring rolling process.
4.1.4 CASE 1d – Driver Roll Speed of 600 rpm

Driver roll speed $n_1 = 600$ rpm, ∴ $a = 0.0006$ and $b = 2258.56$

Table 7

Instantaneous values after each revolution of ring ($n_1 = 600$ rpm)

<table>
<thead>
<tr>
<th>i</th>
<th>$R_i$</th>
<th>$r_i$</th>
<th>$\Delta h_{\text{min}}$</th>
<th>$\Delta h_{\text{max}}$</th>
<th>$\Delta t_i$</th>
<th>$\Delta h_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>61.915</td>
<td>39.685</td>
<td>0.094</td>
<td>1.562</td>
<td>0.059</td>
<td>0.072</td>
</tr>
<tr>
<td>1</td>
<td>61.938</td>
<td>39.721</td>
<td>0.094</td>
<td>1.563</td>
<td>0.059</td>
<td>0.072</td>
</tr>
<tr>
<td>2</td>
<td>61.962</td>
<td>39.758</td>
<td>0.094</td>
<td>1.564</td>
<td>0.059</td>
<td>0.072</td>
</tr>
<tr>
<td>3</td>
<td>61.985</td>
<td>39.794</td>
<td>0.094</td>
<td>1.565</td>
<td>0.059</td>
<td>0.072</td>
</tr>
<tr>
<td>4</td>
<td>62.008</td>
<td>39.831</td>
<td>0.094</td>
<td>1.566</td>
<td>0.059</td>
<td>0.072</td>
</tr>
<tr>
<td>5</td>
<td>62.032</td>
<td>39.867</td>
<td>0.094</td>
<td>1.566</td>
<td>0.059</td>
<td>0.072</td>
</tr>
<tr>
<td>6</td>
<td>62.055</td>
<td>39.903</td>
<td>0.094</td>
<td>1.567</td>
<td>0.059</td>
<td>0.072</td>
</tr>
<tr>
<td>7</td>
<td>62.079</td>
<td>39.940</td>
<td>0.094</td>
<td>1.568</td>
<td>0.059</td>
<td>0.072</td>
</tr>
<tr>
<td>8</td>
<td>62.102</td>
<td>39.976</td>
<td>0.094</td>
<td>1.569</td>
<td>0.059</td>
<td>0.072</td>
</tr>
<tr>
<td>9</td>
<td>62.126</td>
<td>40.013</td>
<td>0.094</td>
<td>1.570</td>
<td>0.059</td>
<td>0.072</td>
</tr>
<tr>
<td>10</td>
<td>62.149</td>
<td>40.049</td>
<td>0.094</td>
<td>1.571</td>
<td>0.059</td>
<td>0.072</td>
</tr>
</tbody>
</table>

Maximum of $\Delta h_{\text{min}} = 0.094$

Minimum of $\Delta h_{\text{max}} = 1.562$

$\Delta h_{\text{Avg}} = 0.080$

Since $\Delta h_{\text{Avg}}$ is smaller value Type.3 deformation behaviour is expected, where there is still a small plastic strain zone near middle radius of the ring blank.
4.2 CASE 2 – Feed Rate is varied with Driver Roll Speed Constant at 160 rpm for Material HE30

Driver roll speed of 160rpm is kept constant and γ is varied

4.2.1 CASE 2a – Feed Rate of 0.5 mm/sec

Feed rate of 0.5mm/sec, \( \therefore a = 0.0009 \) and \( b = 2258.56 \)

\[
\text{Process time, } T = \frac{\Delta H}{\gamma} = \frac{6.2244}{0.5} = 12.5 \text{ Secs}
\]

Table 8

<table>
<thead>
<tr>
<th>( i )</th>
<th>( R_i )</th>
<th>( r_i )</th>
<th>( \Delta h_{\text{min}} )</th>
<th>( \Delta h_{\text{max}} )</th>
<th>( \Delta t_i )</th>
<th>( \Delta h_i )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>61.915</td>
<td>39.685</td>
<td>0.094</td>
<td>1.562</td>
<td>0.222</td>
<td>0.111</td>
</tr>
<tr>
<td>1</td>
<td>62.115</td>
<td>39.996</td>
<td>0.094</td>
<td>1.570</td>
<td>0.222</td>
<td>0.111</td>
</tr>
<tr>
<td>2</td>
<td>62.318</td>
<td>40.310</td>
<td>0.093</td>
<td>1.577</td>
<td>0.223</td>
<td>0.111</td>
</tr>
<tr>
<td>3</td>
<td>62.524</td>
<td>40.628</td>
<td>0.093</td>
<td>1.585</td>
<td>0.224</td>
<td>0.112</td>
</tr>
<tr>
<td>4</td>
<td>62.733</td>
<td>40.950</td>
<td>0.092</td>
<td>1.592</td>
<td>0.224</td>
<td>0.112</td>
</tr>
<tr>
<td>5</td>
<td>62.947</td>
<td>41.276</td>
<td>0.092</td>
<td>1.600</td>
<td>0.225</td>
<td>0.113</td>
</tr>
<tr>
<td>6</td>
<td>63.163</td>
<td>41.606</td>
<td>0.091</td>
<td>1.607</td>
<td>0.226</td>
<td>0.113</td>
</tr>
<tr>
<td>7</td>
<td>63.384</td>
<td>41.939</td>
<td>0.091</td>
<td>1.614</td>
<td>0.227</td>
<td>0.113</td>
</tr>
<tr>
<td>8</td>
<td>63.608</td>
<td>42.277</td>
<td>0.090</td>
<td>1.622</td>
<td>0.228</td>
<td>0.114</td>
</tr>
<tr>
<td>9</td>
<td>63.835</td>
<td>42.619</td>
<td>0.090</td>
<td>1.629</td>
<td>0.228</td>
<td>0.114</td>
</tr>
<tr>
<td>10</td>
<td>64.067</td>
<td>42.966</td>
<td>0.089</td>
<td>1.636</td>
<td>0.229</td>
<td>0.115</td>
</tr>
</tbody>
</table>

Maximum of \( \Delta h_{\text{min}} = 0.094 \)  Minimum of \( \Delta h_{\text{max}} = 1.562 \)

\( \Delta h_{\text{Avg}} = 0.113 \)
Since $\Delta h_{Avg}$ is smaller value Type.3 deformation behaviour is expected, where there is still a small plastic strain zone near middle radius of the ring blank.

### 4.2.2 CASE 2b– Feed Rate of 2.5 mm/sec

Feed rate of 2.5mm/sec, $\therefore a = 0.0045$ and $b = 2258.56$

Process time, $T = \frac{\Delta H}{\gamma} = \frac{6.2244}{2.5} = 2.5$ Secs

**Table 9**

Instantaneous values after each revolution of ring ($\gamma = 2.5$mm/sec)

<table>
<thead>
<tr>
<th>$i$</th>
<th>$R_i$</th>
<th>$r_i$</th>
<th>$\Delta h_{min}$</th>
<th>$\Delta h_{max}$</th>
<th>$\Delta t_i$</th>
<th>$\Delta h_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>61.915</td>
<td>39.685</td>
<td>0.094</td>
<td>1.562</td>
<td>0.222</td>
<td>0.554</td>
</tr>
<tr>
<td>1</td>
<td>62.954</td>
<td>41.287</td>
<td>0.092</td>
<td>1.600</td>
<td>0.225</td>
<td>0.563</td>
</tr>
<tr>
<td>2</td>
<td>64.084</td>
<td>42.990</td>
<td>0.089</td>
<td>1.636</td>
<td>0.229</td>
<td>0.573</td>
</tr>
<tr>
<td>3</td>
<td>65.317</td>
<td>44.807</td>
<td>0.086</td>
<td>1.671</td>
<td>0.234</td>
<td>0.584</td>
</tr>
<tr>
<td>4</td>
<td>66.668</td>
<td>46.755</td>
<td>0.083</td>
<td>1.704</td>
<td>0.239</td>
<td>0.596</td>
</tr>
<tr>
<td>5</td>
<td>68.154</td>
<td>48.851</td>
<td>0.079</td>
<td>1.736</td>
<td>0.244</td>
<td>0.610</td>
</tr>
<tr>
<td>6</td>
<td>69.797</td>
<td>51.119</td>
<td>0.075</td>
<td>1.766</td>
<td>0.250</td>
<td>0.624</td>
</tr>
<tr>
<td>7</td>
<td>71.625</td>
<td>53.586</td>
<td>0.071</td>
<td>1.795</td>
<td>0.256</td>
<td>0.641</td>
</tr>
<tr>
<td>8</td>
<td>73.669</td>
<td>56.290</td>
<td>0.067</td>
<td>1.822</td>
<td>0.264</td>
<td>0.659</td>
</tr>
<tr>
<td>9</td>
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<td>0.272</td>
<td>0.680</td>
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<tr>
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<td>62.598</td>
<td>0.059</td>
<td>1.872</td>
<td>0.281</td>
<td>0.703</td>
</tr>
</tbody>
</table>

Maximum of $\Delta h_{min} = 0.094$  Minimum of $\Delta h_{max} = 1.562$

$\Delta h_{Avg} = 0.617$

Since $\Delta h_{Avg}$ is some what large value Type.1 deformation behaviour is expected as the thickness of the ring reduces rapidly, i.e. the material in the deformation zone comes into the plastic state quite easily.
4.2.3 CASE 2c– Feed Rate of 4 mm/sec

Feed rate of 4mm/sec, ∴ \( a = 0.0072 \) and \( b = 2258.56 \)

Process time, \( T = \frac{\Delta H}{\gamma} = \frac{6.2244}{4} = 1.55 \) Secs

Table 10

Instantaneous values after each revolution of ring (\( \gamma = 4\)mm/sec)

<table>
<thead>
<tr>
<th>( i )</th>
<th>( R_i )</th>
<th>( r_i )</th>
<th>( \Delta h_{\text{min}} )</th>
<th>( \Delta h_{\text{max}} )</th>
<th>( \Delta t )</th>
<th>( \Delta h_i )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
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<td>39.685</td>
<td>0.094</td>
<td>1.562</td>
<td>0.222</td>
<td>0.886</td>
</tr>
<tr>
<td>1</td>
<td>63.630</td>
<td>42.310</td>
<td>0.090</td>
<td>1.622</td>
<td>0.228</td>
<td>0.911</td>
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<tr>
<td>2</td>
<td>65.601</td>
<td>45.220</td>
<td>0.085</td>
<td>1.679</td>
<td>0.235</td>
<td>0.939</td>
</tr>
<tr>
<td>3</td>
<td>67.889</td>
<td>48.480</td>
<td>0.080</td>
<td>1.731</td>
<td>0.243</td>
<td>0.972</td>
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<td>1.779</td>
<td>0.253</td>
<td>1.010</td>
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<td>0.067</td>
<td>1.824</td>
<td>0.264</td>
<td>1.056</td>
</tr>
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<td>1.865</td>
<td>0.278</td>
<td>1.112</td>
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<td>7</td>
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<td>1.272</td>
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<td>9</td>
<td>97.390</td>
<td>85.007</td>
<td>0.037</td>
<td>1.967</td>
<td>0.348</td>
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<td>10</td>
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<td>0.028</td>
<td>1.993</td>
<td>0.393</td>
<td>1.573</td>
</tr>
</tbody>
</table>

Maximum of \( \Delta h_{\text{min}} = 0.094 \)

Minimum of \( \Delta h_{\text{max}} = 1.562 \)

\( \Delta h_{\text{Avg}} = 1.119 \)

Since \( \Delta h_{\text{Avg}} \) is larger value Type.1 deformation behaviour is expected for sure, as the thickness of the ring reduces rapidly, i.e. the material in the deformation zone comes into the plastic state very easily.
4.3 CASE 3 – Effects of Changing the Position Guide Rolls for Material HE30

Guide rolls position changed

Driver roll speed of 600rpm with a feed rate of 1.22mm/sec with the guide rolls position changed.

All the calculations are same as Case.1c except that the guide rolls position is changed.

4.4 Calculation using Material 6061-O

The calculation is same as for material HE30. There is no change in the calculations.

The same calculation will be used for further analysis
CHAPTER 5

RESULTS OF FE ANALYSIS OF COLD RING ROLLING

The decisive factor is identified as average amount of feed per revolution. The main factor contributing the change in average amount of feed per revolution are driver roll speed and the feed rate. The analysis is performed by varying one factor and keeping the other constant. In case 1, the feed rate is kept constant at 1.22 mm/sec and the analysis is performed for driver roll speed of 60, 160, 350 & 600 rpm. In case 2, the driver roll speed is kept constant at 160 rpm and the analysis is performed for feed rate of 0.5, 2.5 and 4 mm/sec.

The results of the analysis are plotted for Effective plastic strain, vonmises stress and KE/IE ratio v/s time. The contours of Effective plastic strain and vonmises stress are plotted at different time intervals. By comparing the contours and the fringe levels the distribution of the plastic strain along the thickness of the ring is studied. The KE/IE ratio v/s time is plotted for each case on the same scale, so that it is easier to compare. The result shows that KE/IE ratio obtained is all lesser than 10%. It is plotted to study the amount of oscillations and the inertial effects during the process.

5.1 CASE 1 - Driver Roll Speed is varied with Feed Rate Constant at 1.22mm/sec for Material HE30

Feed rate of 1.22mm/sec is kept constant and \( n_1 \) is varied

Material 1 - The results of the simulation performed on aluminum alloy HE30 are shown below in terms of Plastic strain plot, Von mises plot and KE/IE v/s time plots.
5.1.1 CASE 1a - Driver Roll Speed of 60 rpm

Driver roll speed \( n_1 = 60 \text{ rpm} \), \( \therefore \Delta h_{\text{Avg}} = 0.808 \text{ mm/rev} \)

By looking at the figure 20 and also the fringe levels in the figure 22 it is clear that there are not many oscillations except at the beginning of the analysis.

The figure 21 shows that the material in deformation zone comes into the plastic deformation state at the early stage of the process. The material at the middle radius of the ring is also deforming into plastic state at initial stage, which leads to homogeneous deformation of the ring i.e., Type 1 PDB

![Figure 20. Plot of KE/IE ratio v/s Time for ring blank of Case 1a](image)

(The plot is scaled by a factor of 1000 in Y-Direction.)
Figure 21. Fringe plots of equivalent plastic strain for Case 1a
Figure 22. Fringe plots of Von mises stress for Case 1a
5.1.2 CASE1b - Driver Roll Speed of 160 rpm

Driver roll speed $n_1 = 160$ rpm, $\therefore \Delta h_{avg} = 0.311$ mm/rev

By looking at figure 23 and the fringe levels of figure 25, it is clear that there are not many oscillations except at the beginning of the analysis which is due to increase in the speed of driver roll.

Figure 24 shows that the material in deformation zone comes into the plastic deformation state at the early stage of the process. The material at the middle radius of the ring is also deforming into plastic state at initial stage, which leads to homogeneous deformation of the ring i.e., Type 1 PDB

![Material Data Graph](image)

Figure 23. Plot of KE/IE ratio v/s Time for ring blank of Case 1b

(The plot is scaled by a factor of 1000 in Y-Direction.)
Figure 24. Fringe plots of equivalent plastic strain for Case 1b
Figure 25. Fringe plots of Von mises stress for Case 1b
5.1.3 CASE 1c - Driver Roll Speed of 350 rpm

Driver roll speed \( n_1 = 350 \text{ rpm} \), \( \therefore \Delta h_{\text{Avg}} = 0.136 \text{ mm/rev.} \)

By looking at figure 26 and the fringe levels of figure 28 it is clear that there are not many oscillations in the Von Mises effective stress. When compared with KE to IE ratio for the Case.1a, there are oscillations, which indicate that at higher rpm of the driver roll speed inertial effects are significant.

Figure 27 shows that the material in deformation zone gradually comes into the plastic deformation state during the process. Even though the material at the middle radius of the ring is at small plastic strain range initially, it gradually comes into plastic deformation state (Type 2) which is clear from the values of the effective plastic strains during the process.

![Figure 26. Plot of KE/IE ratio v/s Time for ring blank of Case 1c](Image)

(The plot is scaled by a factor of 1000 in Y-Direction.)
Figure 27. Fringe plots of equivalent plastic strain for Case 1c
Figure 28. Fringe plots of Von mises stress for Case 1c
5.1.4 CASE 1d - Driver Roll Speed of 600 rpm

Driver roll speed $n_1 = 600$ rpm, $\therefore \Delta h_{\text{Avg}} = 0.080$ mm/rev

By looking at figure 29 and the fringe levels of figure 31, it can be seen that there are significant oscillations in beginning and during the process which is due to driver roll rotating at higher speed. It is also clearly visible from the plot, that the inertial effects are significant after a time of $t=3.2$secs.

Figure 30 shows that there is a rigid zone in elastic deformation or small plastic strain near the middle radius of the ring blank (Type 3) till the time $t=3.2$sec, after this time the inertial effects are observed and the ring is going out of round shape, which is controlled by changing the guide roll position as shown in Case.3.

![Plot of KE/IE ratio v/s Time for ring blank of Case 1d](image.png)

Figure 29. Plot of KE/IE ratio v/s Time for ring blank of Case 1d

(The plot is scaled by a factor of 1000 in Y-Direction.)

This plot is compared with Figure 43 (Guide roll position changed.)
Figure 30. Fringe plots of equivalent plastic strain for Case 1d
Figure 31. Fringe plots of Von mises stress for Case 1d
5.2 CASE 2 - Feed Rate is varied with Driver Roll Speed Constant at 160 rpm for Material HE30

Driver roll rotational speed of 160rpm is kept constant and feed rate is varied.

Material I - The results of the simulation performed on aluminum alloy HE30 are shown below in terms of Plastic strain plot, Von mises plot and KE/IE v/s time plots

5.2.1 CASE 2a - Feed Rate of 0.5 mm/sec

Feed rate $\gamma = 0.5$mm/sec, $\therefore \ \Delta h_{\text{avg}} = 0.113$ mm/rev.

By looking at figure 32 and the fringe levels of figure 34, it is clear that there are not many oscillations except in the beginning of the process.

Figure 33 shows that there is a rigid zone in elastic deformation or small plastic strain near the middle radius of the ring blank throughout the process (Type 3), from the fringe levels it can be seen that plastic strains are small near the middle radius of the ring blank.

![Figure 32. Plot of KE/IE ratio v/s Time for ring blank of Case 2a](image)

(The plot is scaled by a factor of 1000 in Y-Direction.)
Figure 33. Fringe plots of equivalent plastic strain for Case 2a
Figure 34. Fringe plots of Von mises stress for Case 2a
5.2.2 CASE 2b - Feed Rate of 2.5 mm/sec

Feed rate $\gamma = 2.5\text{mm/sec}$, :: $\Delta h_{\text{Avg}} = 0.617\text{ mm/rev}$.

By looking at figure 35 and the fringe levels of figure 37, it is clear that there are not many oscillations in the analysis.

Figure 36 shows that the material in deformation zone comes into the plastic deformation state at the early stage of the process (Type 1).

![Figure 35. Plot of KE/IE ratio v/s Time for ring blank of Case 2b](image)

(The plot is scaled by a factor of 1000 in Y-Direction.)
Figure 36. Fringe plots of equivalent plastic strain for Case 2b
Figure 37. Fringe plots of Von mises stress for Case 2b
5.2.3 CASE 2c - Feed Rate of 4 mm/sec

Feed rate $\gamma = 4\text{mm/sec}$, $\therefore \Delta h_{\text{Avg}} = 1.119 \text{ mm/rev}$

By looking at figure 38 and the fringe levels of figure 40, it is clear that there are not many oscillations in the analysis.

Figure 39 shows that the material in deformation zone comes into the plastic deformation state at the early stage of the process. The material at the middle radius of the ring is also deforming into plastic state at initial stage, which leads to homogeneous deformation of the ring (Type 1).

![Image](image.png)

Figure 38. Plot of KE/IE ratio $v/s$ Time for ring blank of Case 2c

(The plot is scaled by a factor of 1000 in Y-Direction.)
Figure 39. Fringe plots of equivalent plastic strain for Case 2c
Figure 40. Fringe plots of Von mises stress for Case 2c
5.3 CASE3- Effect of Changing the Position of Guide Rolls for Material HE30

Driver roll speed of 600rpm with a feed rate of 1.22mm/sec with the guide rolls position changed.

Figure 41. 2D model showing the guide rolls position changed.
(Compared with Figure 17)

Figure 42. Fringe plots of equivalent plastic strain for Case 3
The guide roll position is changed as shown in figure 41. In figure 42, it shows small plastic strain state near the middle radius of the ring, and also the ring has lost its original shape to form a non-circular ring as the final product.

Figure 43. Plot of KE/IE ratio v/s Time for ring blank of Case 3

(The plot is scaled by a factor of 1000 in Y-Direction.)

When compared with the figure 29 which shows the KE to IE ration for case 1c it is clear that the inertial effects are not reduced but increases. So the position of guide rolls does not have any effects.
5.4 CASE 1 - Driver Roll Speed is varied with Feed Rate Constant at 1.22mm/sec for Material 6061-O

Feed rate of 1.22mm/sec is kept constant and $n_1$ is varied

Material II - The results of the simulation performed on aluminum alloy 6061-O are shown below in terms of KE/IE v/s time plot, Plastic strain plot, Von mises plot

5.4.1 CASE 1a - Driver Roll Speed of 60 rpm

Driver roll speed $n_1 = 60$ rpm, $\therefore \Delta h_{Avg} = 0.808$ mm/rev.

By looking at figure 44 and the fringe levels of figure 46, it is clear that there are not many oscillations except at the beginning of the analysis.

Figure 45 shows that the material in deformation zone comes into the plastic deformation state at the early stage of the process. The material at the middle radius of the ring is also deforming into plastic state at initial stage, which leads to homogeneous deformation of the ring (Type 1).

![Figure 44. Plot of KE/IE ratio v/s Time for ring blank of Case 1a](image)

(The plot is scaled by a factor of 1000 in Y-Direction.)
Figure 45. Fringe plots of equivalent plastic strain for Case 1a
Figure 46. Fringe plots of Von mises stress for Case 1a
5.4.2 CASE 1b - Driver Roll Speed of 160 rpm

Driver roll speed $n_1 = 160$ rpm, $\therefore \Delta h_{\text{Avg}} = 0.311$ mm/rev.

By looking at figure 47 and the fringe levels of figure 49, it is clear that there are not many oscillations except at the beginning of the analysis which is due to increase in the speed of driver roll.

Figure 48 shows that the material in deformation zone comes into the plastic deformation state at the early stage of the process. The material at the middle radius of the ring is also deforming into plastic state at initial stage, which leads to homogeneous deformation of the ring i.e., Type 1 PDB

![Figure 47. Plot of KE/IE ratio v/s Time for ring blank of Case 1b](image)

(The plot is scaled by a factor of 1000 in Y-Direction.)
Figure 48. Fringe plots of equivalent plastic strain for Case 1b
Figure 49. Fringe plots of Von mises stress for Case 1b
5.4.3 CASE 1c - Driver Roll Speed of 350 rpm

Driver roll speed \( n_1 = 350 \text{ rpm} \), \( \therefore \Delta h_{\text{Avg}} = 0.136 \text{ mm/rev.} \)

By looking at figure 50 and the fringe levels of figure 52, it is clear that there are a small amount of oscillations which is due to increase in the speed of driver roll.

Figure 51 shows that the material in deformation zone gradually comes into the plastic deformation state during the process. Even though the material at the middle radius of the ring is at small plastic strain range initially, it gradually comes into plastic deformation state (Type 2) which is clear from the values of the effective plastic strains during the process. When compared with KE to IE ratio for the Case.1a, there are oscillations, which indicate that at higher rpm of the driver roll speed inertial effects are significant.

Figure 50. Plot of KE/IE ratio v/s Time for ring blank of Case 1c

(The plot is scaled by a factor of 1000 in Y-Direction.)
Figure 51. Fringe plots of equivalent plastic strain for Case 1c
Figure 52. Fringe plots of Von mises stress for Case 1c
5.4.4 CASE 1d - Driver Roll Speed of 600 rpm

Driver roll speed \( n_1 = 600 \) rpm, \( \therefore \Delta h_{\text{Avg}} = 0.080 \) mm/rev

By looking at figure 53 and the fringe levels of figure 55, it can be seen that there are significant oscillations during the ring rolling process. It clearly visible from the plot, that the inertial effects are significant after a time of \( t=3.2\) secs.

Figure 54 shows that there is a rigid zone in elastic deformation or small plastic strain near the middle radius of the ring blank (Type 3) till the time \( t=3.2\)sec, after this time the inertial effects are observed along with localized biting, due to which the ring is losing its original circular shape.

![Figure 53. Plot of KE/IE ratio v/s Time for ring blank of Case 1d](image)

(The plot is scaled by a factor of 1000 in Y-Direction.)
Figure 54. Fringe plots of equivalent plastic strain for Case 1d
Figure 55. Fringe plots of Von mises stress for Case 1d
5.5 CASE 2 - Feed Rate is varied with Driver Roll Speed Constant at 160 rpm for Material HE30

Driver roll rotational speed of 160rpm is kept constant and feed rate is varied.

Material II - The results of the simulation performed on aluminum alloy 6061-O are shown below in terms of KE/IE v/s time plot, Plastic strain plot, Von mises plot

5.5.1 CASE 2a - Feed Rate of 0.5 mm/sec

Feed rate $\gamma = 0.5$mm/sec, $\therefore \Delta h_{\text{Avg}} = 0.113$ mm/rev.

By looking at figure 56 and the fringe levels of figure 58, it is clear that there are not many oscillations during the process of ring rolling except at the beginning.

Figure 57 shows that there is a rigid zone in elastic deformation or small plastic strain near the middle radius of the ring blank throughout the process (Type 3), from the fringe levels it can be seen that plastic strains are small near the middle radius of the.

![Figure 56. Plot of KE/IE ratio v/s Time for ring blank of Case 2a](image)

(The plot is scaled by a factor of 1000 in Y-Direction.)
Figure 57. Fringe plots of equivalent plastic strain for Case 2a
Figure 58. Fringe plots of Von mises stress for Case 2a
5.5.2 CASE 2b - Feed Rate of 2.5 mm/sec

Feed rate $\gamma = 2.5$ mm/sec, $\therefore \Delta h_{\text{Avg}} = 0.617$ mm/rev.

By looking at figure 59 and the fringe levels of figure 61, it is clear that there are not many oscillations during the process.

Figure 60 shows that the material in deformation zone comes into the plastic deformation state at the early stage of the process (Type 1).

CASE 2b. Feed rate $\gamma = 2.5$ mm/sec, $\therefore \Delta h_{\text{Avg}} = 0.617$ mm/rev.

Figure 59. Plot of KE/IE ratio v/s Time for ring blank of Case 2b

(The plot is scaled by a factor of 1000 in Y-Direction.)
Figure 60. Fringe plots of equivalent plastic strain for Case 2b
Figure 61. Fringe plots of Von mises stress for Case 2b
5.5.3 CASE 2c - Feed Rate of 4 mm/sec

Feed rate $\gamma = 4$mm/sec, $\therefore \Delta h_{\text{Avg}} = 1.119$ mm/rev

By looking at figure 62 and the fringe levels of figure 64, it is clear that there are not many oscillations during the process. The oscillation shown in this plot is lesser when compared to other cases.

Figure 63 shows that the material in deformation zone comes into the plastic deformation state at the early stage of the process. The material at the middle radius of the ring is also deforming into plastic state at initial stage, which leads to homogeneous deformation of the ring (Type 1).

---

Figure 62. Plot of KE/IE ratio v/s Time for ring blank of Case 2c

(The plot is scaled by a factor of 1000 in Y-Direction.)
Figure 63. Fringe plots of equivalent plastic strain for Case 2c
Figure 64. Fringe plots of Von mises stress for Case 2c
CHAPTER 6
DISCUSSION AND COMPARISON

6.1 Plastic deformation behavior

Under first type of plastic deformation behaviour the material comes to plastic state at the early stage of the process resulting in easy flow of metal in circumferential direction, under second type deformation behaviour since at the early stage of the process there is a rigid zone in elastic deformation or small plastic strain state near the middle radius of the ring blank, it just rotates without any expansion thus restricting ring blank to grow in diameter, but as the process goes on the rigid region slowly disappears. Under third type of deformation behaviour there is always a rigid zone with elastic strain or small plastic strain state near the middle radius of the ring blank it prevents ring from expanding in diameter, by turning the metal flow to the axial direction, which is not desirable since the ring rolling is carried out to expand the diameter of the ring, and axial rolls are used to restrict increase in ring height.

By comparing the fringe plots of plastic strain, at t = 0.39s for Case.1a, 1b 1c and 1d of both materials as shown in figure 65 and figure 66.

\[
\Delta h_{\text{Avg}} = 0.808 \text{ mm/rev} \quad \Delta h_{\text{Avg}} = 0.136 \text{ mm/rev} \quad \Delta h_{\text{Avg}} = 0.136 \text{ mm/rev} \quad \Delta h_{\text{Avg}} = 0.113 \text{ mm/rev}
\]

Figure 65. Fringe plots of plastic strain of material HE30 at t = 0.39s
Comparing how the material deforms for different amount of feed per revolution ($\Delta h_{\text{Avg}}$), the material deforms uniformly through thickness of the ring for higher values $\Delta h_{\text{Avg}}$, and the deformation is not homogeneous for lower values of $\Delta h_{\text{Avg}}$. The deformation behaviour is similar to the deformation behaviour observed in the previous literature for corresponding $\Delta h_{\text{Avg}}$.

Therefore it is preferred to have Type.1 deformation behaviour, which is achieved by providing large value of average amount of feed per revolution, which is useful in causing the metal to flow in circumferential direction, have homogeneous deformation and to avoid internal cracks and surface cracks in the deformed ring, which is clear from the results obtained in all the cases.

By comparing the fringe plots of plastic strain at $t = 5.2$ secs for Case.1a, 1b, 1c and 1d of both the materials as shown in figure 67 and figure 68.

Figure 66. Fringe plots of plastic strain of material 6061-0 at $t = 0.39$ s

Figure 67. Fringe plots of plastic strain of HE30 at $t = 5.2$ s
Comparing how the material deforms for different amount of feed per revolution ($\Delta h_{\text{Avg}}$), it is clear that for less $\Delta h_{\text{Avg}}$ event at the end of the process there exist a zone of small plastic strain near the middle radius of the ring. For $\Delta h_{\text{Avg}} = 0.113 \, \text{mm/rev}$ the fringe plot is not clear as there are some inertial effects which is making the ring non circular.

### 6.2 Plastic strain

The obtained strain values are lower in case of 350rpm and 600rpm of driver roll speed, because under these conditions the material tends to flow in axial direction of the ring because of type.2 and type.3 deformation behavior, in which the ring expansion is restricted because of elastic or small plastic strain state zone. Since the analysis is carried out under plane strain condition the material flow in axial direction is not there and Z-strain (change in height) will be zero so the effective strain will be less. The maximum effective strain of both the materials is compared with the literature as shown in Table 11.
Table 11

Maximum effective plastic strain

<table>
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<tr>
<th>Driver roll speed in rpm</th>
<th>Time</th>
<th>Maximum effective Plastic strain</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<td>HE30</td>
</tr>
<tr>
<td>60</td>
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<td></td>
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<td></td>
<td>1.56</td>
<td>0.244</td>
</tr>
<tr>
<td></td>
<td>3.51</td>
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</tr>
<tr>
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</tr>
<tr>
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<td>0.39</td>
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</tr>
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6.3 Resultant Driver roll force

When the plane strain element formulation is performed using numerical analysis code LSDYNA, by default it assumes the thickness 1, but in actual it is 25.4mm. Since the results have to be compared with the literature the plots are scaled by the ring height 25.4mm.

From all four plots, it can seen that when the average amount of feed per revolution is high the roll force is high, because the material in the deformation zone comes into plastic state at the early stage of the process and power required for deformation is high, whereas when \( \Delta h_{\text{Avg}} \) is less there is elastic zone or small plastic strain state which reduces the amount of material participating in plastic deformation, which requires less power to produce plastic deformation.

The oscillation in the curve can be mainly of two aspects. One is that the complex and dynamic boundary conditions during the cold ring rolling process will lead to oscillation, and the other is that the cold ring rolling process belongs to the non-steady state deformation process, so the size of the plastic deformation continuously changes during the operation.

In the material 6061-O plots, the obtained curve differs to the literature when compared to the material HE30 curve. It can be due to approximation of the material constant in the constitutive. And since the 6061 alloy is comparatively very soft when compared to the HE30.
Figure 69. Plot of roll force v/s Time (comparison b/n HE30 and literature)

Figure 70. Plot of roll force v/s Time (all cases of HE30)
Figure 71. Plot of roll force v/s Time (comparison b/n 6061-O and literature)

Figure 72. Plot of roll force v/s Time (all cases of 6061-O)
CHAPTER 7
CONCLUSION AND RECOMMENDATION

7.1 Conclusions

The following conclusions are given based on the research:

- The decisive factor on plastic deformation behavior, namely the average amount of feed per revolution has first been ascertained. The initial values of process parameters for developing the FE model of cold ring rolling are selected.

- The distribution of the strain field in the deforming ring has been obtained by using 2D-FE simulation based on dynamic explicit FEM. And the plastic deformation behavior in cold ring rolling has been explored. The influence of plastic deformation behavior on driver roll force is also explored. The simulation is repeated using another class of aluminum alloy. The results reveal the deformation mechanism of cold ring rolling.

- It is required to have higher average amount of feed per revolution to achieve homogeneous deformation throughout the thickness of the ring blank, in order to avoid internal cracks and to improve the quality of the rolled ring. It is required to have average amount of feed per revolution greater than 0.6 mm/revolution.

- It is suggested to operate at lower rotational speed of driver roll and high feed rate (Fast idle roll movement in thickness direction) to achieve required amount of average amount of feed per revolution in order to reduce the inertial effects during the process. From the results (KE to IE ratio) shown for case.2 study i.e. 160 rpm
of driver roll speed it can be seen that the inertial effects are less. The driver roll speed of 160 rpm and a feed rate of 4mm/sec give the best results.

- The roll force and power required increases with the increase in average amount of feed per revolution, as more power is required to deform the material in the deformation zone. The roll force required for homogeneous deformation to occur in material HE30 is 55 KN and in material 6061-O is 118 KN.

7.2 Recommendations

To expand the research further the following recommendations are given:

- To study the plastic deformation behavior by performing the FE analysis using a different class of alloy
- To study about inertial effects that play a significant role at higher rotating speed of driver roll
- To study localized biting at higher speed of driver roll
- To study the 3D FE analysis of ring rolling process by considering the axial deformation


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