Analysis of asymmetric cold rolling using finite element method to create flat sheet

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Abstract

In this paper, a simulation of asymmetric cold rolling is being presented by using an explicit analysis procedure. A two-dimensional finite element model with adaptive meshing technique has been employed to simulate asymmetrical condition, due to difference of the roll radius and velocity. Some conditions have been found to make sheet without curvature, in order to achieve this goal, different velocities have been made in rolls in each radius ratio. To validate the simulation, the results of the simulation has been compared with experimental papers which was done in the past. The effects of asymmetric process have been discussed, which is caused by radius ratio and velocity ratio on the rolling force, rolling torque and on the sheet curvature. Also the optimum velocity ratio in each radius ratio that causes the sheet without curvature was obtained. It was found that the appropriate speed ratio to produce flat sheets (i.e. sheets without curvature) is almost 1.067 being independent of the radius ratios between 1 and 1.05.

Keywords: Asymmetrical Rolling; Finite Element Method; Radius Ratio; Velocity Ratio; Sheet Curvature; Flat Sheet

Introduction

lately, asymmetric rolling process is used a lot. asymmetric process has some advantages over symmetric one, for example such asymmetric rolling process decreases rolling force but it can make deflection in sheet, and this phenomenon can be advantageous When the target is a curved sheet, R. Shivpuri and et al. [1] investigated on curling sheets due to roll speed mismatch. But when the target is a sheet without curvature, it will cause problems, therefore a lot of research has been done to predict the curvature of such sheets. W. Johnson and G. Needham [2, 3] had some empirical studies on asymmetric rolling process. In these experiments different roll diameters was applied. They also found that direction of sheets curvature always is toward to the roll of which has the lower peripheral velocity. They also did further experiments to determine the rolling force, rolling torque and sheets curvature; and compared the results with each other. Since raising and declining of the sheets can be troublesome during their production, therefore S. A. E. Buxton and S. C. Browning [4] have investigated on raising and decreasing phenomena and determine the main factors governing the phenomena. P. Dewhurst et al. [5] investigated on asymmetrical hot rolling to predict the sign and magnitude of the curvature of the rolled strip. In [6] asymmetric plane, strain of rolled plate was analyzed by using finite element method. They generate different interface friction for two rolls. And found that the sheets curvature is toward to the roll with highest friction. Y. M. Hwang and T. H. Chen [7] also proposed a mathematical model for asymmetrical rolling. They obtained the rolled curvature under various roll speed
ratio, roll radius ratio, friction factor ratio, and inlet angle of the sheets. Hwang [8,9] used an analytical model to investigate the stress field of the clad gap. For this model they used sticking friction and Dimensionless numbers like roll speed ratio, frictional factor ratio, roll radius ratio and etc. to be applicable in different situations. In another article they used two models to investigate rolling force and torque; in the first model they have considered the effect of shear stress in vertical plate while they ignored this effect in second model. they compared their results with experimental results which they had achieved in 1997 [10]. J. S. Lu and et al. [11] simulated asymmetric rolling by using finite element method. They showed the effects of different diameters of the working rolls and the degree of reduction of the sheets on bending of the work piece. M. Salimi and F. Sassani [12] used another analytical model based on the slab method of analysis and developed it to obtain the characteristics of asymmetrical sheet rolling to predict sheet curvature. Salami and Kadkhodaei [13, 14] obtained an equation which predict the required external loading sheet to produce horizontal sheet, and in the other paper they have predicted the deflection of plate with genetic algorithm and compared the results to experimental investigations. Gudur [15] also have generated computer codes to estimate the curvature and then compared the results to previous simulation done by himself. Qwamizadeh and Salimi [16] tried to estimate plate curvature, they calculated this curvature based on differences in shear and normal strain in upper and lower section of sheets. S.H. Zhang [17] calculated the rolling force and rolling torque in asymmetrical sheet rolling using analytical solution where analytical method was based on the Slab method. They compare their result with experimental and theoretical result in Hwang paper [10] and Qwamizadeh [16] theoretical result. Su-Wen Chen [18] developed slab method to calculate the rolling force, rolling torque and neutral point with considering the properties of large cylindrical shell rolling. They consider different surface temperatures, normal and shear stress. A. Aboutorabi [19] investigated the horizontal displacement effect on rolling force and torque of rolls, and they obtain formula which calculate the sheet curvature induced by rolls horizontal displacement. Sun [20], use an analytical model based on slab method to calculate the force parameters in asymmetrical cylinder rolling where the rolls radius, speeds, friction and contact arc lengths are different. And also, they calculated the curvature at the exit of deformation zone of heavy cylinder rolling. On the other hand, some other researchers were looking for ways to reduce curvature; like J. Pospiech [21] who have investigated on factors affecting the curvature of a cold rolled sheet and shown that under some circumstances a straight sheet could be created even with asymmetrical condition. H. Liang [22] used finite element method by ALE adaptive meshing technique to simulate cold asymmetric rolling, because they were trying to find straight sheets. According to a research conducted in the past asymmetric rolling, decrease the rolling force and rolling torque but it creates curvature in the sheet. So far, many methods to calculate rolling force and torque also, sheet curvature are presented, but little research in the field has been done to reduce the sheet curvature or make sheet without curvature. In this paper cold asymmetric rolling was simulated to find a method to make straight sheet, to this aim an asymmetric radial has been made and in each ratio of the radius, an asymmetric velocity has been made; Another advantage that was obtained in this process is the decrease of the main rolling force as well as the upper and lower torques. In this method the advantages of the process are maintained while it eliminates the disadvantages of that, like deformation of the sheet.
The Finite Element Models

Finite Element Method (FEM) is a method to analyze numerical solution of mechanical problems. The current problem requires that to be determined by spatial distribution of one or more dependent variables. In this study a FEM has been used as commercial based software, ABAQUS 6.13, to simulate the asymmetric cold rolling. To decrease the size of the model and due to symmetrical geometry of the sheet and rolls, 2D model has been considered in our simulation. Since the Eulerian model is not able to predict the deformation due to appropriate process, an explicit Lagrangian model has been used.

Modeling of Asymmetric Rolling

Fig. 1 shows the schematic of asymmetric rolling. The figure also shows the positions of the neutral points. When the radius ratio or speed ratio of the upper roller and lower roller are different it is clear that the position of the neutral points will not be the same at the top and bottom points in X axis; So the area of plastic deformation can be divided into three distinct parts. In this paper, the indices u and l were used for upper roll and lower roll, respectively. The rolling setup consisted of two rolls which are rigid and non-deformable. $R_u$ and $R_l$ have been defined as the upper and lower rolls radius where $h_i$ and $h_o$ are the initial and final plate thickness, respectively. It is assumed that the lower roller radius (speed) is more than the upper roller radius. So that in the area I, the upper and lower surface friction stress directions are the same with sheet velocity. In the area II, sheet speed is more than the upper roller speed and less than the lower roller’s speed, so the upper surface friction’s stress acts in the opposite direction but lower surface friction stress acts in the same direction. In the zone III, both surface friction stress acts in the opposite direction, since the speed of both the upper and lower roller is less than sheet velocity.

Validation of the Simulation Results

Mesh Dependency Study

To validate the simulations, dependency analysis has been meshed and it has shown that further growth in the density of the mesh has little effect on the outputs. In order to find a mesh independence solution, nine numerical simulations with different mesh density was conducted (Table 1); and it was found that the optimum model has 6250 quadrilateral elements. To analyze mesh independency, vertical rolling force of one of the rolls was applied (Fig. 2). Figure 3 is a sample of sheet meshing.

Validation of the Simulation Results
The rolling parameters obtained from the simulations, were compared to the experimental studies of reference [10] and theoretical studies of [10, 16]. The material parameters and the condition of the simulation were similar to those used in references [10, 16]. To validate the rolling force, the experimental results of reference [10] was employed (see Fig. 4). The effects of reduction on rolling force were depicted in Fig. 4. The analytical results of reference [10, 16] are also indicated in the graph. There exist great similarities among our simulations and other experimental and theoretical results.

**Specifications of Simulated Models**

All the simulations were performed by assuming that constant friction coefficient is 0.359 for the upper and lower part of the sheet surface. In addition, the linear velocity of the upper roll was presumed to be constant and equaled to $V = 0.556$ m/s. The top roll radius was assumed to be constant and equaled to $R_u = 105$ mm. The reduction percentage was assumed to be 10 for all simulations. The asymmetry was produced by changing the linear velocity and radius of the lower rolls. In this paper, the curvature is positive when the Y axis is in the negative direction which is shown in Fig. 5. The sheet was intended to be deformable and plane strain, which Table 2 summarizes the properties of the aluminum alloy and geometry parameters.

**RESULTS AND DISCUSSION**

Fig. 6 to Fig. 9 shows the effects of the asymmetric condition on rolling force and rolling torque, and Fig. 10 shows the variation of sheet curvature with the linear velocity ratio for six radius ratio of 1, 1.01, 1.02, 1.03, 1.04 and 1.05. in order to discuss, problem have been reviewed from the beginning when the rollers are symmetric. (Fig. 11)

As it’s shown in the Fig.7, it is specified that in symmetric mode neutral points of both the upper and lower parts are in same position, it means that before the plotted line, sheet speed is less than roller linear speed; so the rollers generate friction force on the sheet. The speed of the sheet and rollers liners speed are equal on the plotted line, so there isn’t any interaction between them. In the next part of the line, since the roller speed is less than sheet’s speed, the friction force acts in opposite direction of sheet’s speed, So:

\[ f_{u1} = f_{l1} \] (2)
\[ f_{u2} = f_{l2} \] (3)

Due to the low correlation, the upper and lower torques are equal to each other:

\[ M_u = (f_{u1} - f_{u2})R_u \] (4)

By increasing the radius of the lower roller (Or increasing the rotational speed), the linear velocity of the lower roller surface increases, which makes The neutral point of the lower roller to go ahead and the upper Roller neutral point moves backward. (Fig. 12)
When the lower roller neutral point moves ahead, the length of the roller surface which has higher velocity than sheet’s velocity, increases, so friction force in this area increases. It means that $f_{12}$ increases, but on the contrary $f_{12}$ decreases.

As a result, lower roller torque Increases, according to the following formula:

$$M_1 = (f_{11} - f_{12})R_1$$  \(4\)

But in the upper Roller situation, the neutral point is transmitted to the rear and the length of that part of surface which roller’s speed is more than sheet’s speed, decreases. As a result $f_{u1}$ decreased and $f_{u2}$ is increased so according to the formula 4 the upper roller torque is decreased. With further increase of the ratio of the radius (or velocity) The neutral point is moved backward as far as the friction force in both sides of the neutral point will be equal to each other ($f_{u1} = f_{u2}$); in this condition upper roller torque will be equal to zero. By following the mentioned process, (increasing radius ratio or velocity ratio) the neutral point is moved backward and it causes $f_{u1} > f_{u2}$: As a result the upper roller torque will become negative.

It should be noted that although reducing the force and torque is one of the advantages in the asymmetric rolling, producing the sheet with no curvature is preferable. It is also advisable to produce the zero curvature sheet with lower force and torque. Therefore, the study was further conducted to found the optimum linear velocity in order to create the zero curvature sheet in the asymmetric rolling.

First, one can imagine that the sheet must be bent toward the roller which has a lower speed. Since the linear velocity of the upper roller surface is less than that of the lower roller surface, so the sheet must be bent upwardly. As the velocity vector of lower surface of the sheet is greater than the velocity vector of the upper surface therefore the sheet will be bent upward, as shown in Fig.13. But unlike the first imagination, by increasing the radius ratio (or speed ratio) the sheet is bent downward, but if the radius ratio increased further, the sheet is bent upward.

To interpret this process, the position of the neutral point must be noticed. the neutral point is the point where linear velocity of the roller and that of sheet is equal. Assume that the radius ratio (or speed ratio) is equal to $r_A$, so when the linear velocity of the upper roller is equal to $V$ then the linear velocity of the lower roller is $V \times r_A$; therefore the upper neural point velocity is $V$ and the lower one is $V \times r_A$. When $r_A$ is very small, approximately a specified length of sheets in both asymmetric and symmetric modes are rolled simultaneously. So it can be concluded that the average speed of both modes is equal to each other. In Fig. 14 A and C points are neural in asymmetric mode, Similarly B and E points are neural in the symmetric mode. As in the case of symmetric mode, the linear speed of upper and lower rollers is equal , it can be concluded that in the case of symmetric mode the linear velocity on the line BE is constant and equal to $V$.

Since the speed of symmetric and asymmetric mode in the middle part of the sheet should be equal, then the velocity of point G in two modes is V. Since the sheet thickness is very small, it can be assumed that the velocity profile of the sheet is linear. the velocity of point A which is the neural point of the upper roller and it is also equal to V, so by drawing lines AG and extending it to point D it can be concluded that the speed of the line AD is equal to V.
According to the mentioned definitions, the velocity of point F must be less than the velocity of point D, because point F is located before point D. So it can be concluded that on line AF the upper points of the line have more velocity than the lower ones. So it can be said that the average velocity of the upper points of the sheet is more than that of the lower points which are located on the sheet. So the average velocity of each side that is lower, the sheet will be bent to the same side. By increasing the radius ratio (velocity ratio) further, the horizontal distance between two neural points increases and average velocity difference between the top and bottom of the sheet surface increases to reach its maximum. In this case, the curvature of the sheet which its direction is downward will reach to its maximum value. But then by further increase of radius ratio (or speed ratio) the neutral points almost proved to be constant. But by increasing the radius ratio (or speed ratio) the velocity average of lower roller will be increased. This process continues until the average velocity of the upper and lower parts of the sheet will be equal to each other; and in this special radius ratio (or speed ratio) the sheet will be produced almost horizontally without inflection.

CONCLUSIONS
In this paper, the asymmetric rolling was investigated and analyzed by the finite element method. Effects of asymmetry are discussed because of the roll radius ratio and speed ratio on rolling force and torque. The simulation results in a great extent verify the past experiments and theoretical studies. The following conclusions can be drawn:

- by increasing the speed ratio rolling vertical force is reduced.
- By increasing the radius ratio rolling vertical force is increased.
- By increasing the speed (or radius) ratio of both upper and lower Rolling torque is reduced.
- By increasing the radius ratio total Rolling torque is increased.
- In each radius ratio by increasing speed ratio total torque treated differently.
- In lower radius ratio by increasing speed ratio total torque is reduced.
- In higher radius ratio by increasing speed ratio total torque is increased.
- For each radius ratio, an optimum speed ratio was calculated to produce flat sheet and it is shown in Table3.
- By increasing radius ratio optimum velocity ratio, was almost constant and equal to 1.067.
- As can be seen in Fig. 9 to Fig. 14 by increasing the radius ratio, the part which contains maximum curvature is reduced.

Reference


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Table 1: Mesh refinement sensitivity
Table 2: Summarizes the properties and geometry
Table 3: Optimum Speed Ratio

Fig. 1 schematic of asymmetric rolling
Fig. 2. Mesh refinement sensitivity
Fig. 3. Two Dimensional Grid
Fig. 4. Comparison of rolling force predicted by the present model with other researchers, Result: \( R_u = 50 \text{mm}, \ R_t = 105 \text{mm}, \ m_u = m_t = 0.359, \ h_t = 2 \text{mm}, \ V_A = 1.05, \ \sigma_{x1} = \sigma_{x0} = 0 \)
Fig. 5. The schematic of positive curvature
Fig. 6. Schematic of symmetric rolling
Fig. 7. Schematic move the neutral point
Fig. 8. Velocity Vector of Surface
Fig. 9. Schematic of Neural Point in Symmetry and Asymmetry Mode
Fig. 10. Force against speed ratio for radius ratio between 1 to 1.05 ($R_u = 105mm$.

$m_u = m_t = 0.359, h_i = 2mm, \sigma_{x1} = \sigma_{x0} = 0$

Fig. 11. Upper roller torque against speed ratio for radius ratio between 1 to 1.05 ($R_u = 105mm$.

$m_u = m_t = 0.359, h_i = 2mm, \sigma_{x1} = \sigma_{x0} = 0$

Fig. 12. Lower roller torque against speed ratio for radius ratio between 1 to 1.05 ($R_u = 105mm$.

$m_u = m_t = 0.359, h_i = 2mm, \sigma_{x1} = \sigma_{x0} = 0$

Fig. 13. Total roller torque against speed ratio for radius ratio between 1 to 1.05 ($R_u = 105mm$.

$m_u = m_t = 0.359, h_i = 2mm, \sigma_{x1} = \sigma_{x0} = 0$

Fig. 14. Sheet curvature against speed ratio for radius ratio 1 to 1.05 ($R_u = 105mm, m_u = m_t = 0.359, h_i = 2mm, \sigma_{x1} = \sigma_{x0} = 0, r = 10$)

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<th>Sheet Force (KN/mm)</th>
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<tr>
<td>(2)</td>
<td>125</td>
<td>0.695</td>
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<tr>
<td>(3)</td>
<td>250</td>
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<td>(5)</td>
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<tr>
<td>The final thickness of the sheet</td>
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<td>$E$</td>
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<td>10%</td>
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</table>
Fig. 1

Fig. 2

Fig. 3
Fig. 4

Fig. 5

Fig. 6

Fig. 7
Fig. 12

Fig. 13

Fig. 14