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Analysis of asymmetric cold rolling using finite-element method for creating flat sheet

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Flat sheet.

Abstract. In this paper, asymmetric cold rolling is simulated using an explicit analysis procedure. A two-dimensional finite element model with an adaptive meshing technique has been employed to simulate asymmetrical condition due to the 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 considered in rolls in each radius ratio. To validate the simulation, the results of the simulation have been compared with experimental papers, as done in the past. The effects of asymmetric process, caused by radius ratio and velocity ratio, on the rolling force, rolling torque, and the sheet curvature have been analyzed and discussed. In addition, the optimum velocity ratio in each radius ratio that causes the sheet without curvature has been obtained. It has been found that an appropriate speed ratio to produce flat sheets (i.e., sheets without curvature) is almost 1.067, independent of the radius ratios between 1 and 1.05.

1. Introduction

Lately, the asymmetric rolling process has received much attention for use. It enjoys some advantages over symmetric one. For example, this process decreases rolling force, yet can make deflection in sheet, and this phenomenon is advantageous when the target is a curved sheet. Shivpuri et al. [1] investigated curling sheets with respect to the roll speed mismatch. However, when the target is a sheet without curvature, it leads to problems; therefore, much research has been done to predict the curvature of such sheets. Johnson and Needham [2,3] conducted some empirical studies on the asymmetric rolling process. In these experiments, different roll diameters were applied. They found that direction of sheets' curvature was always toward the roll with lower peripheral velocity. In addition, they carried out further experiments to determine the rolling force, rolling torque, and sheets curvature; then, they compared the results with each other. Since raising and declining of the sheets can be troublesome during their production, Buxton and Browning [4] investigated raising and decreasing phenomena and determined the main factors governing the phenomena. Dewhurst et al. [5] investigated the asymmetrical hot rolling to predict the sign and magnitude of the curvature of the rolled strip. In asymmetric plane [6], strain of rolled plate was analyzed using finite element method. They generated different interface frictions for two rolls, and found that the sheets' curvature was toward the roll with the highest friction. Hwang and Chen [7] proposed a mathematical model for asymmetrical rolling. They obtained the rolled

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curvature under various roll speed ratios, roll radius ratios, friction factor ratios, and inlet angles of the sheets. Hwang and Tzou [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, such as roll speed ratio, frictional factor ratio, roll radius ratio, etc., so that they can be applicable to different situations. In another article, they used two models to investigate rolling force and torque; in the first model, they considered the effect of shear stress on vertical plate, while they ignored this effect in the second model. They compared their results with experimental results, achieved in 1997 [10]. Lu et al. [11] simulated asymmetric rolling 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. Salimi and 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. Salimi and Kadkhodaei [13] and Kadkhodaei et al. [14] obtained an equation that predicts the required external loading sheet to produce horizontal sheet; in another paper, they predicted the deflection of plate with genetic algorithm and compared the results to experimental investigations. Gudur et al. [15] also generated computer codes to estimate the curvature and, then, compared the results to previous simulation done by himself. Qwamizadeh et al. [16] tried to estimate plate curvature and calculated this curvature based on differences in shear and normal strains in the upper and lower sections of sheets. Zhang et al. [17] calculated the rolling force and rolling torque in asymmetrical sheet rolling using analytical solution where the analytical method was based on the slab method. They compared their result with experimental and theoretical results in Hwang's paper [10] and Qwamizadeh's [16] theoretical result. Chen et al. [18] developed slab method to calculate the rolling force, rolling torque, and neutral point considering the properties of large cylindrical shell rolling. They considered different surface temperatures as well as normal and shear stresses. Aboutorabi et al. [19] investigated the horizontal displacement effect on rolling force and torque of rolls and obtained a formula to calculate the sheet curvature induced by rolls horizontal displacement. Sun et al. [20] used 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 were different. In addition, they calculated the curvature at the exit of deformation zone of heavy cylinder rolling. On the other hand, some other researchers have looked for ways to reduce curvature; for instance, Pospiech [21] investigated the factors affecting the curvature of a cold rolled sheet, and showed that a straight sheet could be created even with the asymmetrical condition under some circumstances. Liang et al. [22] used finite element method by the 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 decreased the rolling force and rolling torque; however, it created curvature in the sheet. So far, many methods have calculated rolling force and torque as well as sheet curvature. Nevertheless, few researches in the field have 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 was made; in each ratio of the radius, an asymmetric velocity was made. Another advantage 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 its disadvantages, such as deformation of the sheet, are eliminated.

2. The finite element models

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

3. Modeling of asymmetric rolling

Figure 1 shows the schematic of asymmetric rolling. The figure also shows the positions of the neutral

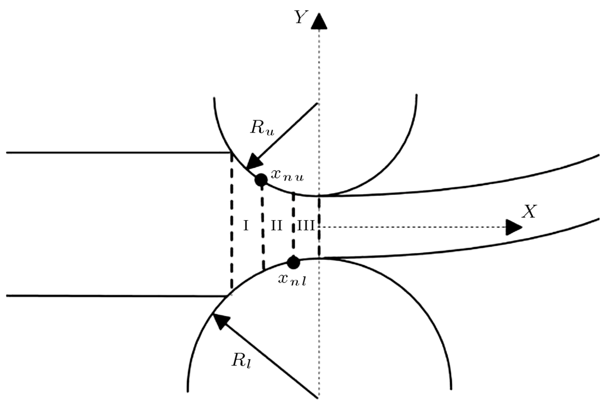

Figure 1. Schematic of asymmetric rolling.

points. When the radius ratio or speed ratio of the upper roller and lower roller is 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. Therefore, the area of plastic deformation can be divided into three distinct parts. In this paper, indices u and l are used for upper roll and lower roll, respectively. The rolling setup consists of two rolls: rigid and non-deformable. R_u and R_l are defined as the upper and lower rolls' radii, where h_i and h_0 are the initial and final plate thicknesses, respectively. It is assumed that the lower roller radius (speed) is higher than the upper roller radius. Therefore, in area I, the upper and lower surface friction stress directions are the same with sheet velocity. In area II, sheet speed is higher than the upper roller speed and lower than the lower roller's speed; therefore, the upper surface friction's stress acts in the opposite direction; therefore, the lower surface friction's stress acts in the same direction. In zone III, both surface friction stresses act in the opposite direction, since the speed of both the upper and lower rollers is less than that of sheet velocity.

4. Validation of the simulation results

4.1. Mesh dependency study

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

4.2. 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 [10,16]. To validate the rolling force, the experimental results of [10] were employed (see Figure 4). The effects of reduction on rolling force are depicted in Figure 4. The analytical results [10,16] are also shown in the graph. There exist great similarities among our simulations and other experimental and theoretical results.

Table 1. Mesh refinement sensitivity.

Mesh case	Number of element	Sheet force (kN/mm)
(1)	100	0.549
(2)	125	0.695
(3)	250	0.769
(4)	1000	0.808
(5)	1850	0.820
(6)	4000	0.791
(7)	**6250**	**0.780**
(8)	10000	0.797
(9)	16000	0.775

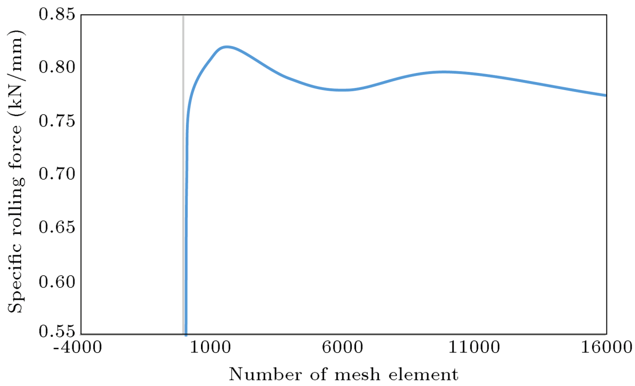

Figure 2. Mesh refinement sensitivity.

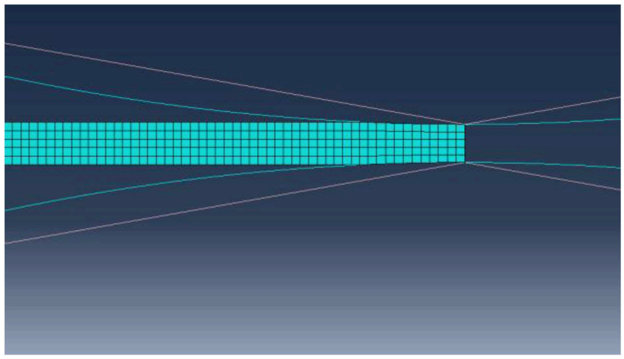

Figure 3. Two-dimensional grid.

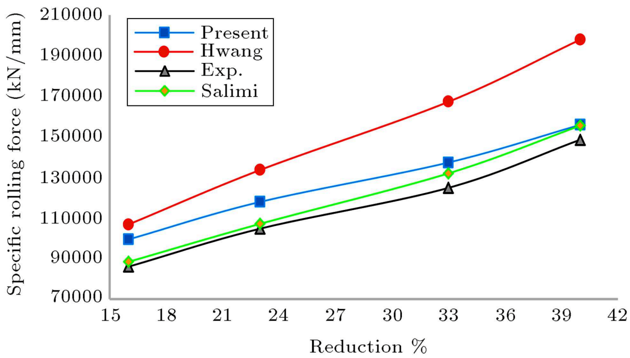

Figure 4. Comparison of rolling force predicted by the present model with those of other research studies (result: $R_u = 50$ mm, $R_l = 105$ mm, $m_u = m_l = 0.359$, $h_i = 2$ mm, $V_A = 1.05$, $\sigma_{x1} = \sigma_{x0} = 0$).

4.3. Specifications of simulated models

All the simulations were performed by considering constant friction coefficient as 0.359 for the upper and

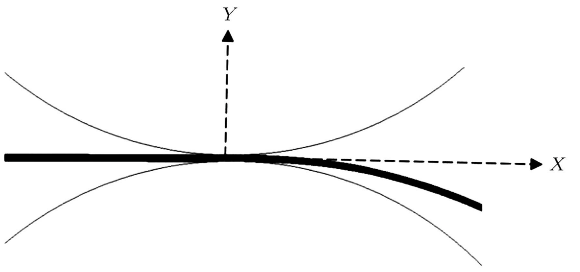

Figure 5. The schematic of positive curvature.

lower parts of the sheet surface. In addition, the linear velocity of the upper roll was presumed to be constant and equal to $V = 0.556$ m/s. The top roll radius was assumed to be constant and equal to $R_u = 105$ mm. The reduction percentage was assumed 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 Y axis is in the negative direction, which is shown in Figure 5. The sheet was intended to be deformable and plane strain. Table 2 summarizes the properties of the aluminum alloy and geometry parameters.

5. Results and discussion

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

As is shown in Figure 7, it is specified that, in the symmetric mode, neutral points of both upper and lower parts are in the same position, meaning that, before the plotted line, sheet speed is lower than roller linear speed; therefore, the rollers generate friction force on the sheet. The speed rates of the sheet and

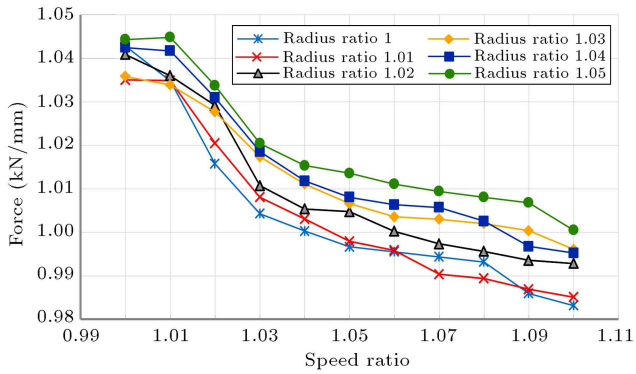

Figure 6. Schematic of symmetric rolling.

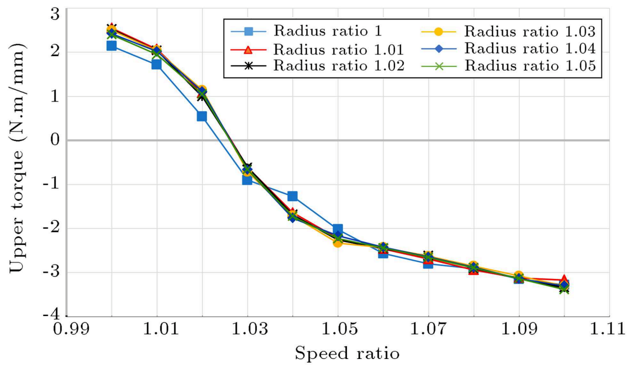

Figure 7. Schematic of the neutral point movement.

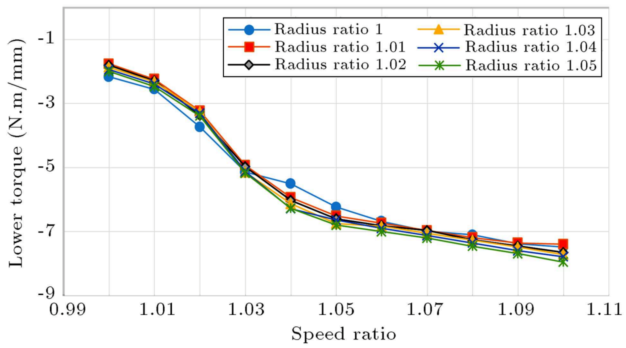

Figure 8. Velocity vector of surface.

Table 2. Summary of the properties and geometry.

Parameter	Symbol	Magnitude
The initial thickness of the sheet	h_i	2 mm
The final thickness of the sheet	h_0	1.8 mm
Upper roll radius	R_u	105 mm
Upper roll Rotational velocity	V_u	5.3 rad/s
Young's modulus	E	70 GPa
Poisson's ratio	ϑ	0.3
Mass density	ρ	2710 kg/m^3
Yield stress	σ_y	170 MPa
constant friction coefficient	μ	0.359
Percentage reduction	r	10%
the sheet width	w	100 mm

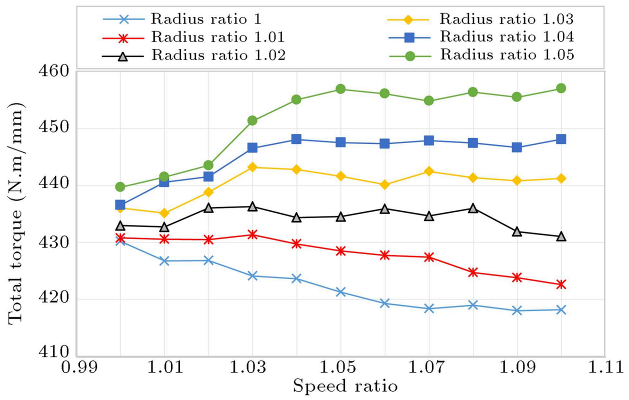

Figure 9. Schematic of neutral point in symmetry and asymmetry mode.

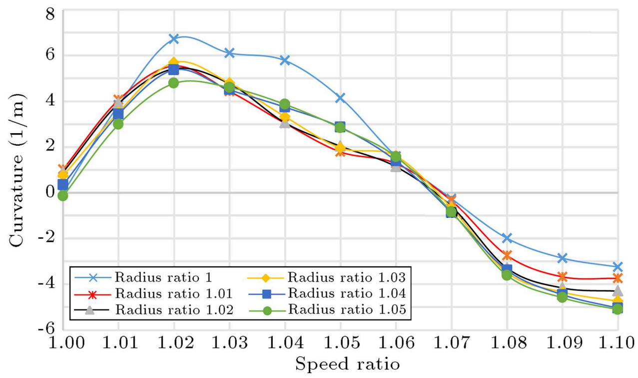

Figure 10. Force against speed ratio for radius ratios between 1 to 1.05 ($R_u = 105$ mm, $m_u = m_l = 0.359$, $h_i = 2$ mm, $\sigma_{x1} = \sigma_{x0} = 0$).

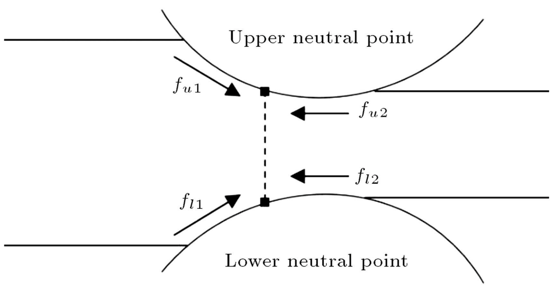

Figure 11. Upper roller torque against speed ratio for radius ratios between 1 to 1.05 ($R_u = 105$ mm, $m_u = m_l = 0.359$, $h_i = 2$ mm, $\sigma_{x1} = \sigma_{x0} = 0$).

rollers liners are equal on the plotted line; therefore, there is not any interaction between them. In the next part of the line, since the roller speed is lower than sheet's speed, the friction force acts in the opposite direction to sheet's speed. Therefore:

$$f_{u1} = f_{l1}, \tag{1}$$

$$f_{u2} = f_{l2}. \tag{2}$$

Due to the low correlation, the upper and lower torques

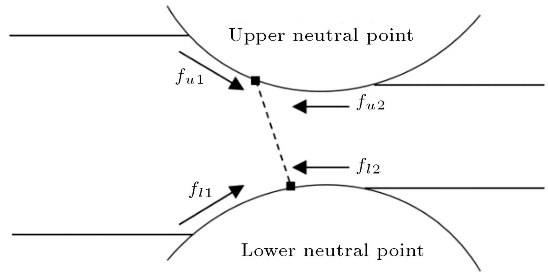

Figure 12. Lower roller torque against speed ratio for radius ratios between 1 to 1.05 ($R_u = 105$ mm, $m_u = m_l = 0.359$, $h_i = 2$ mm, $\sigma_{x1} = \sigma_{x0} = 0$).

are equal:

$$M_u = (f_{u1} - f_{u2})R_u. \tag{3}$$

By increasing the radius of the lower roller (or increasing the rotational speed), the linear velocity of the lower roller surface increases, which allows the neutral point of the lower roller to go ahead, and the upper roller neutral point moves backward (Figure 12).

When the lower-roller neutral point moves ahead, the length of the roller surface, with velocity higher than sheet's velocity, increases; thus, friction force in this area increases. It means that while f_{l1} increases, f_{l2} decreases.

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

$$M_l = (f_{l1} - f_{l2})R_l. \tag{4}$$

However, in the upper roller situation, the neutral point is transmitted to the rear, and the length of that part of surface, on which roller's speed is more than sheet's speed, decreases. As a result, f_{u1} decreases, while f_{u2} increases. Therefore, according to Eq. (4), the upper roller torque decreases.

With further increase of the ratio of the radius (or velocity), the neutral point moves backward as far as the friction force on both sides of the neutral point are equal to each other ($f_{u1} = f_{u2}$); in this condition, upper roller torque is equal to zero. By following the mentioned process, (increasing radius ratio or velocity ratio), the neutral point moves backward, resulting in $f_{u1} > f_{u2}$. As a result, the upper roller torque becomes negative.

It should be noted that although reducing the force and torque is one of the advantages of 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 is further conducted to find 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 with a lower speed. Since the

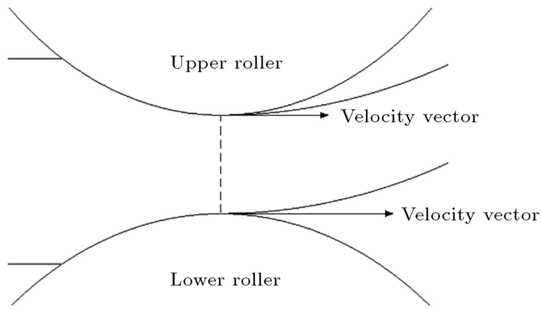

Figure 13. Total roller torque against speed ratio for radius ratios between 1 to 1.05 ($R_u = 105$ mm, $m_u = m_l = 0.359$, $h_i = 2$ mm, $\sigma_{x1} = \sigma_{x0} = 0$).

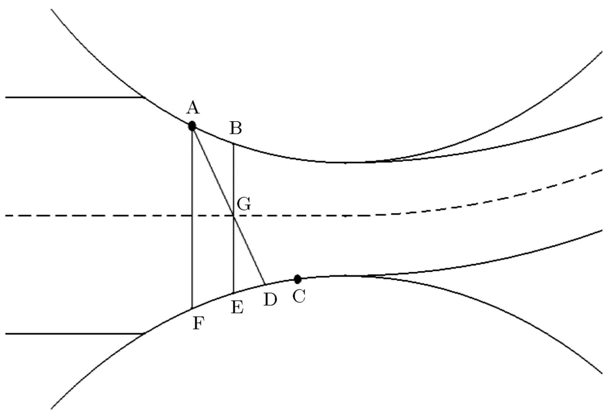

Figure 14. Sheet curvature against speed ratio for radius ratios 1 to 1.05 ($R_u = 105$ mm, $m_u = m_l = 0.359$, $h_i = 2$ mm, $\sigma_{x1} = \sigma_{x0} = 0$, $r = 10$).

linear velocity of the upper roller surface is less than that of the lower roller surface, the sheet must be bent upwardly. Since the velocity vector of lower surface of the sheet is greater than that of the upper surface, the sheet will be bent upward, as shown in Figure 13. However, unlike the first imagination (or speed ratio), the sheet is bent downward by increasing the radius ratio; however, if the radius ratio increases 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 rates of the roller and that of sheet are equal. It is assumed that the radius ratio (or speed ratio) is equal to r_A. Therefore, when the linear velocity of the upper roller is equal to V, the linear velocity of the lower roller is $V \times r_A$; therefore, the upper neutral 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 is rolled simultaneously. Therefore, it can be concluded that the average speeds of both modes are equal. In Figure 14, points A and C are neutral in the asymmetric mode. Similarly, points B and E are neutral 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 modes in the middle part of the sheet should be equal, the velocity of point G in the two modes is V. Since the sheet thickness is very small, the velocity profile of the sheet is linear, as assumed. The velocity of point A is the neutral point of the upper roller and is equal to V; therefore, by drawing lines of 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 lower than that of point D, because point F is located behind point D. Therefore, on line AF, the upper points of the line have more velocity than the lower ones do. Therefore, the average velocity of the upper points of the sheet is more than that of the lower points, located on the sheet. Therefore, the average velocity of each side is lower, and the sheet will be bent towards the same side. By increasing the radius ratio (velocity ratio) further, the horizontal distance between the two neutral points increases, and the difference in average velocity between the top and bottom of the sheet surface increases to reach its maximum. In this case, the curvature of the sheet whose direction is downward will reach its maximum value. Then, by increasing radius ratio (or speed ratio) further, the neutral points almost proved constant. However, by increasing the radius ratio (or speed ratio), the velocity average of lower roller will increase. This process continues until the average velocity of the upper and lower parts of the sheet becomes equal to each other. In this particular radius ratio (or speed ratio), the sheet will be produced almost horizontally without inflection.

6. Conclusions

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

- By increasing the speed ratio, rolling vertical force reduced;
- By increasing the radius ratio, rolling vertical force increased;
- By increasing the speed (or radius) ratio of both upper and lower parts, rolling torque reduced;
- By increasing the radius ratio, total rolling torque increased;

Table 3. Optimum speed ratio.

Radius ratio	1	1.01	1.02	1.03	1.04	1.05
Speed ratio	1.06831	1.06828	1.06692	1.06732	1.06633	1.06663

- In each radius ratio, by increasing speed ratio, the total torque behaved differently;
- In lower radius ratio, by increasing speed ratio, the total torque reduced;
- In higher radius ratio, by increasing speed ratio, total torque increased;
- For each radius ratio, an optimum speed ratio was calculated to produce flat sheet, as shown in Table 3;
- By increasing radius ratio, optimum velocity ratio was almost constant and equal to 1.067;
- Based on Figures 9-14, by increasing the radius ratio, the part that contains maximum curvature reduced.

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