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Research Paper

Experimental Analysis and Numerical Simulation of Asymmetric Rolling Process of Metal Sheets

Hengameh Rezaie[1], Heshmatollah Haghighat[1*]
[1]Mechanical Engineering Department, Razi University, Kermanshah, Iran
[*]Email of the Corresponding Author: hhaghighat@razi.ac.ir
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Abstract
In this research, the three-dimensional asymmetric rolling process of metal sheets has been investigated by experimental and finite element simulation methods. Six aluminum sheet samples with a thickness of six millimeters and different widths were subjected to asymmetric rolling tests. The tests were performed using an asymmetric rolling machine with two different roll diameter ratios. The sheet width and its curvature radius at the exit were measured. In order to obtain the true stress-strain curve of aluminum at room temperature, a simple tensile test was performed. The effects of the asymmetry of the process and the percentage of thickness reduction on the sheet width and curvature radius were investigated. Three-dimensional numerical simulation of the process was performed in DEFORM 3D. The sheet width and curvature radius of the sheet were extracted. The data obtained from the experimental method, including the sheet width and radius of curvature of the exit sheet, were compared with the numerical simulation results. Good agreement was observed between the simulation results and the experimental findings. The results showed that by increasing the ratio of the initial width of the sheet to the thickness, the curvature radius remains constant. Also, as the thickness-reduction percentage increases, the curvature radius decreases and the width of the output sheet increases.

Keywords
Asymmetric Rolling, Experiment, Finite Element Simulation, Curvature Radius, Output Sheet Width

1. Introduction

During the rolling process, the thickness of the metal sheet is reduced by passing through the space between two cylindrical rolls with parallel axes that rotate in opposite directions. In the asymmetric sheet rolling process, the radius or angular velocity of the upper roll is different from that of the lower roll. Usually, in the rolling process, the deformation of the sheet is assumed to be plane strain, that is, the width of the sheet at the exit is equal to the initial width of the sheet. However, when the increase in the width of the sheet cannot be ignored, the deformation of the sheet must be analyzed in three dimensions. In this process, when the ratio of the width to the initial thickness of the sheet is less than 10, the increase in the width cannot be ignored [1]. Since there is a possibility of curvature of the output sheet in the asymmetric rolling process, it is of great importance to predict and control the width of the sheet and the curvature radius of the output sheet to obtain the desired dimensions of the

sheet. The curvature radius of the output sheet can be an important feature in the design. Examples of the applications of the curvature of the output sheet can be the curvature radius that may be used to create piston rings and coil springs. Therefore, two important design features that precisely determine the geometric characteristics of the final sheet, the width and the radius of curvature of the output sheet, must be studied to provide control over them.
So far, much research has been done on this process by various researchers. Komori [2] analyzed the three-dimensional symmetric rolling process of a bar using the upper bound method. He investigated the effects of reducing the thickness and radius of the rolls on increasing the width of the sheet, the rolling torque and the rolling force. Richelsen and Tvergaard [3] analyzed the three-dimensional rolling process to investigate the effect of increasing the width during rolling. In addition, the effect of different values of the width of the sheet and the radius of the roll was investigated. In their proposed model, friction forces in the rolling direction and the transverse direction were considered. Akbari Mousavi et al. [4] studied the effect of the roll speed ratio on the stress distribution and curvature of the sheet. Sezek et al. [5] modeled the 3D symmetric sheet rolling process. They predicted the amount of sheet width increase at the exit using the upper bound method and a 3D velocity field. Gudur et al. [6] estimated the friction coefficient in the asymmetric sheet rolling process by calculating the curvature of the exit sheet. They used the force balance method in their analysis. Qwamizadeh et al. [7] analyzed the asymmetric sheet rolling and predicted the curvature of the exit sheet. Liu et al. [8] proposed a velocity field and presented an upper bound method to calculate the torque and force in the 3D symmetric sheet rolling process. Aboutorabi et al. [9] studied the effect of horizontal displacement of the rolls. They divided the deformation zone into four regions and calculated the force applied to the rolls, the torque and the curvature of the output sheet. Masrouri and Parvezi [10] analyzed the asymmetric rolling process of a non-uniform two-layer sheet using the slab method. Their main goal was to investigate the simultaneous effect of front and rear tension and asymmetric parameters on the distribution of vertical stress and pressure along the contact surface of the rolls. Yaghoobi et al. [11] investigated the microstructure and mechanical properties of two-phase steel produced by asymmetric rolling. They studied the effect of intercritical annealing temperature and time on the microstructure and mechanical properties of the produced two-phase steel. Graca and Vincze [12] reviewed the research conducted on the numerical simulation method of asymmetric sheet rolling. Lv et al. [13] experimentally investigated the curvature of the output sheet in the asymmetric plane strain sheet rolling process. Wang and Liu [14] presented an analytical model using the force balance method to calculate the minimum achievable sheet thickness in the asymmetric sheet rolling process. Zhao et al. [15] analyzed the asymmetric sheet rolling process using the force balance method. They investigated the effects of the speed ratio of the rolls, the thickness of the input sheet, and the friction coefficient on the asymmetric sheet rolling process. Zhao et al. [16] analyzed the asymmetric sheet rolling process to investigate the force and torque of the process. Their model was based on the force balance method and numerical simulation, assuming plane strain as the process. In addition, they also analyzed the process experimentally to verify the validity of their analysis. Su et al. [17] investigated the bending behavior of sheets during asymmetric rolling process by experiment and finite element simulation under plane strain condition. They found that when the roll speed ratio is high and the thickness reduction is small, the sheet bends towards the roll at a slower speed. Su et al. [18] investigated the effect of asymmetric rolling process parameters on the bending

behavior of aluminum sheets. They presented a two-dimensional finite element model for the asymmetric rolling process and compared the rolling test results with the finite element results. The validation of the rolling simulation showed a very good agreement between the simulation and experimental tests. Jiang et al. [19] presented an analytical model for asymmetric rolling of two-layer sheet using the upper bound method. The accuracy of their model was verified by simulation and experiment. Jiang et al. [20] presented an analytical model to predict the curvature of the output sheet based on the non-uniform distribution of shear stress. To demonstrate the validity of their model, they compared the results with experimental and simulation results. Their model could well predict the effective process parameters on the curvature of the bimetallic sheet. Attanasio et al. [21] investigated the sheet rolling process with two numerical and analytical methods to calculate the distribution of roll pressure, force, and process torque. They presented a relationship between the shear friction constant and the friction coefficient in the rolling process. The results of their proposed model showed a good agreement with the experimental results of other researchers. Rezaie and Haghighat [22] presented a new deformation model for analyzing the asymmetric sheet rolling process under plane strain conditions based on the force balance method. In their proposed model, similar to the symmetric sheet rolling process, the sheet material between the upper and lower rolls is divided into two deformation zones. The entry and exit zones were separated from each other by a line connecting the upper and lower neutral points. The validity of their proposed model was assessed by comparing the results with the experimental data of other researchers and the simulation data obtained by the DEFORM software. Flanagan et al. [23] used the finite element method to study the precise stress and strain variation in sheet rolling. They assessed the accuracy of a number of FE approaches, and found that at least 60 elements through-thickness were needed to properly resolve through-thickness variation.

In this paper, the three-dimensional asymmetric sheet rolling process is investigated by experimental and numerical methods. Pure aluminum was used as the test material for the metal sheets. A simple tensile test was used to determine the actual stress-strain behavior of the aluminum material. The effects of the percentage of thickness reduction and the ratio of the initial width to thickness of the sheet on the output sheet width and the radius of curvature of the deformed sheet were investigated. The simulation of the asymmetric sheet rolling was performed using the finite element software DEFORM 3D. The sheet width and the radius of curvature of the output sheet were compared with the results obtained from the finite element simulation method.

2. Experiments

The asymmetric rolling process of a metal sheet is shown in Figure 1. The upper and lower rolls rotate around their axes at angular speeds ω_u andω_l, respectively. The sheet with an initial thickness w_i and an initial width $h_i$enters the space between two rolls with radii R_u و and R_l and exits with a thickness h_f and a final widthw_f. In the asymmetric process, the output sheet may exit with a curvature. The curvature of the output sheet is shown in Figure 1 as$R$. The two-horsepower asymmetric rolling machine designed and built for the purpose of conducting asymmetric rolling process experiments is

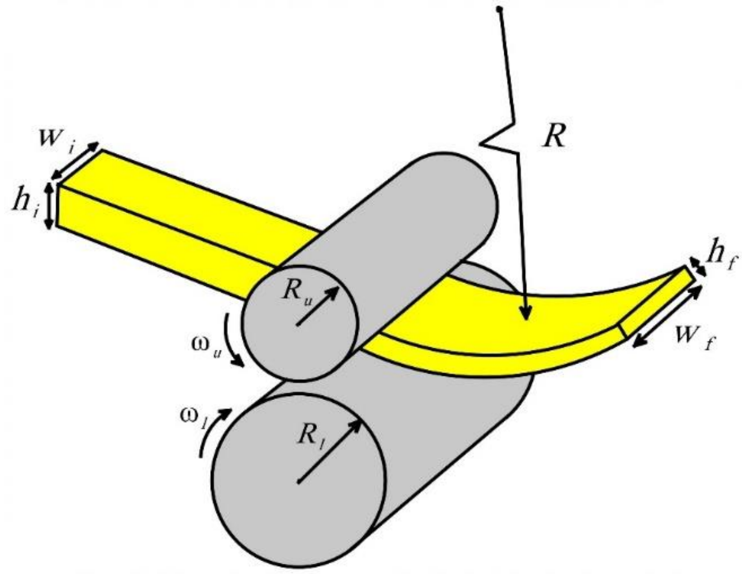
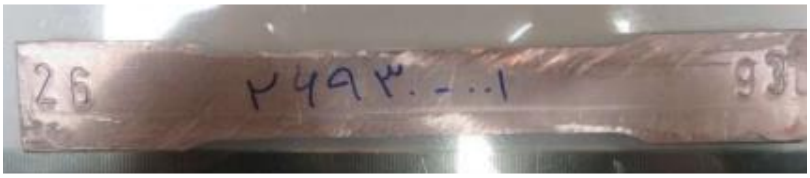


Figure 1. Asymmetrical sheet rolling process

shown in Figure 2. Using these rolls, the roll diameter ratio $R_l = 1.285R_u$was considered for the experiment. All rolling experiments were performed for the same angular speeds of five revolutions per minute for both the lower and upper rolls. A total of nine experiments were conducted in this study. It is worth mentioning that more experiments were repeated to obtain more reliable results. The sheet material used in this study was a commercially pure aluminum (AA1100).

Figure 2. Asymmetrical sheet rolling machine

In order to obtain the stress-strain curve of aluminum material at room temperature, a simple tensile test was performed on the aluminum specimen with a GOTECH tensile testing machine model GT-7001-LC-100. Tensile test specimens were prepared in accordance with ASTM E8 standard. Figure 3 shows the specimen before and after the simple tensile test. The true stress-strain curve after the simple tensile test was obtained as shown in Figure 4.



(a)

(b)

Figure 3. Tensile test specimen (a) Before testing (b) After testing

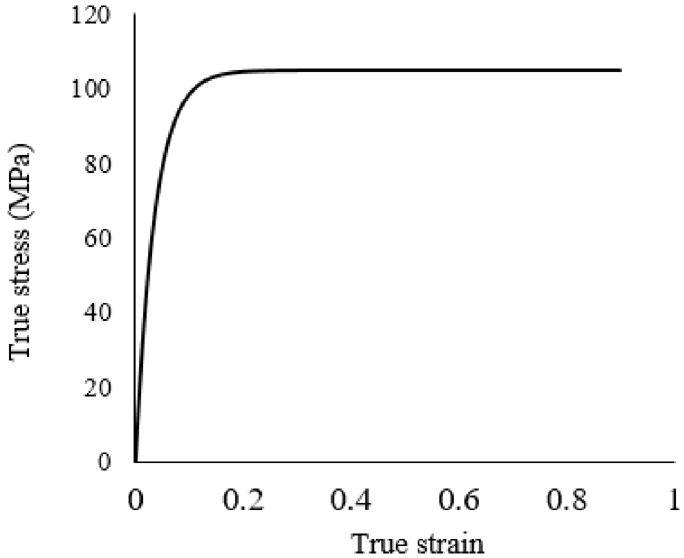
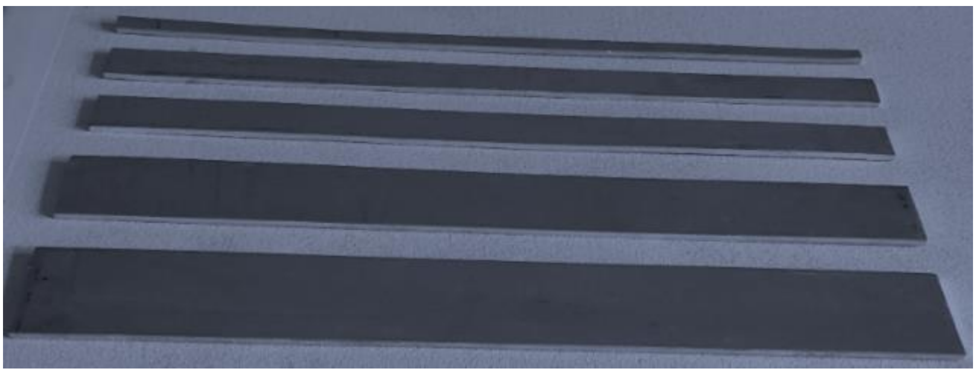
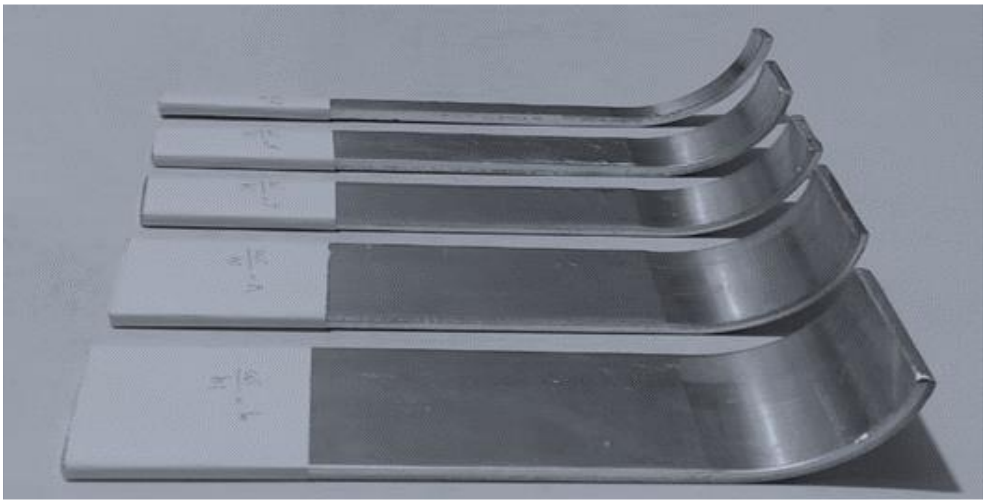


Figure 4. True stress-strain curve of pure aluminum material

The aluminum sheet samples had a rectangular cross section with a thickness of 6 mm, as shown in Figure 5a. The width to thickness ratios of the sheets were selected to be 2, 4, 6, 8, and 10. The sheets were prepared with a length of 500 mm and cleaned with carbon tetrachloride before rolling. Aluminum sheets after the asymmetric rolling process are also shown in Figure 5b.



(a)



(b)

Figure 5. Aluminum sheets a) Before rolling b) After rolling

3. FE Simulation

The DEFORM 3D software was used to simulate the asymmetric rolling process of sheet metal. The DEFORM is a finite element method-based software designed to simulate various metal forming processes. The user-friendly graphical environment of this software and the ease of data preparation and analysis help researchers to focus more on the forming problem and not get involved in tedious computer processes. The first step in simulating the asymmetric rolling process is to draw the different parts and create the process geometry. The initial sheet has a length of 100, an initial thickness of 6, and a width of 12 mm. The final thickness of the sheet is obtained according to the percentage reduction in the sheet thickness. The upper and lower rolls are drawn as cylinders with diameters of 70 and 90 mm, respectively, as shown in Figure 6. After modeling the roll and the sheet, the mechanical properties of the sheet must be determined. Determining the mechanical behavior is one of the most fundamental steps of the simulation. In this analysis, the rolls are rigid and the sheet material is ductile, and its material properties is determined according to the obtained stress-strain curve. In the next step, the sheet meshing is performed. In meshing a metal sheet, the mesh size cannot be chosen arbitrarily. The finer the mesh size is chosen up to a certain limit, the more accurate the output results will be and the conditions will be closer to the real state. In the finite element model, a mesh number of 15,000 has been used. It is worth noting that the software does not mesh for rigid bodies, so the rolls do not need to be meshed. When the parts are defined, they need to be placed in the appropriate positions. The parts must be placed together in such a way that the friction properties required for them can be defined in a desirable way. Therefore, using the five available positioning methods, the modelling of parts is carried out in the FE software environment. The initial sheet must be placed exactly between the two rolls and the surfaces that are in contact with each other during the rolling process must be specified and the contact must be considered separately for each one and the corresponding friction coefficient value must be taken into account. That is, one contact must be defined for the contact surface of the sheet with the upper roll and another contact must be defined for the sheet with the lower roll surface. The friction coefficient between both rolls and the sheet is assumed to be the same and equal to 0.3 [24]. In the next step, the boundary conditions must be specified. The upper and lower rolls have only angular motion, which is applied to them by selecting the center of the rolls, a constant angular velocity of 5 rpm is applied to them. In the case of the 3D rolling process, half of the model is designed to save time in solving the problem and due to the symmetry of the process with respect to the x-y plane. Therefore, since the simulation is symmetrical with respect to the x-y plane, half the width of the sheet is modeled. That is, the width of the cross-section will be 6 mm. This sheet should be constrained in the z-axis direction in the boundary condition definition section and only have movement in the x and y axes. Figure 6 shows the sheet and rolls in three dimensions.

The basis of numerical simulation is the definition of simulation conditions, including the definition of simulation stop and start, process conditions and process control, which is done in the next step. For this purpose, the number and amount of simulation step increase must be determined.

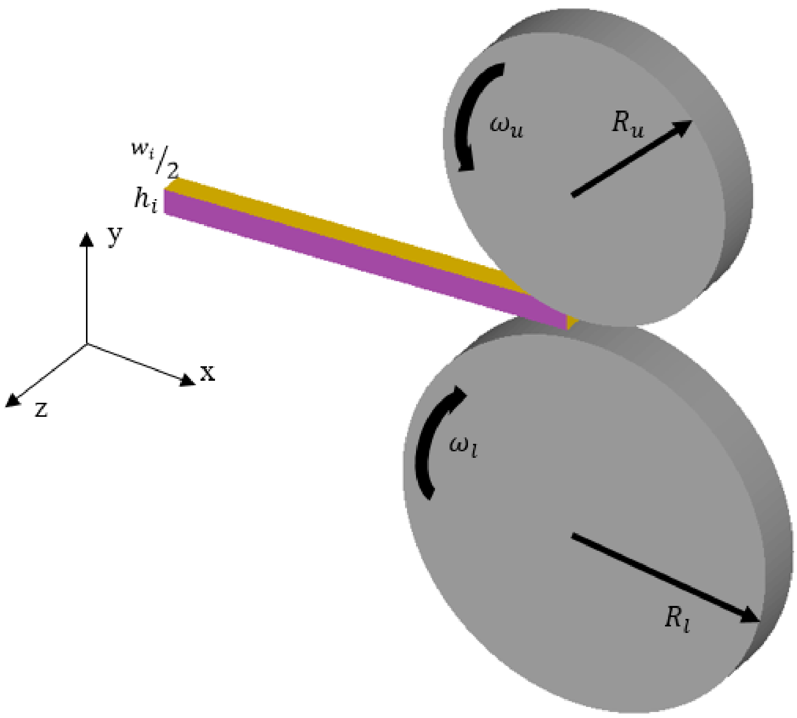


Figure 6. 3D finite element model of the sheet and rolls before deformation

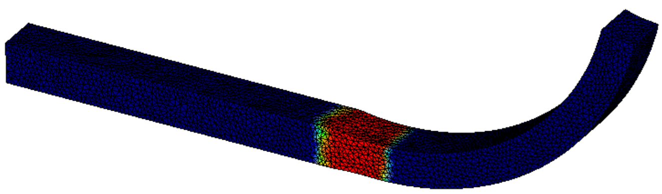


Figure 7. Curvature of the sheet after passing through the rolls

After the information required for simulation is entered into the software, the sheet and rolls are drawn, and the contact conditions between the parts are defined, the input information and error detection are reviewed, and depending on the size of the problem, it will take a certain amount of time to perform the analysis. After completing the problem solving process, the DEFORM 3D software simulates the problem and analyzes it using the finite element method, and all the desired results can be extracted in the DEFORM software environment. Figure 7 shows the simulated sample after the rolling process.

4. Results

In the simulation and experimental method, the value of the curvature radius can be calculated using the following equation [24]:

$$R = \frac{4C^2 + L^2}{8C} \tag{1}$$

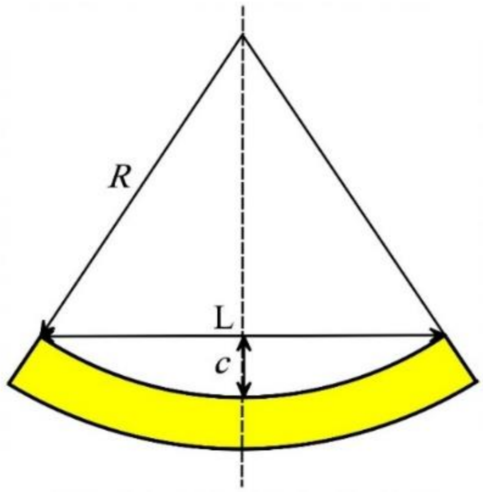


Figure 8. Curvature radius of the output sheet

Where R is the curvature radius of the sheet. L and c are defined as shown in Figure 8.
The simulations were performed assuming a friction coefficient of 0.3 for the upper and lower surfaces of the sheet [24]. A constant angular velocity of 5 rpm and the radii of the lower and upper rolls were taken as 35 and 45 mm, respectively.
The effect of the ratio of the initial sheet width to the initial sheet thickness on the curvature of the output sheet is shown in Figure 9. The initial sheet thickness is fixed at 6 mm and the percentage of thickness reduction is 15%. From this figure, it can be seen that when this ratio increases, the radius of curvature remains constant. This figure also shows that there is a very good agreement between the experimental results and the finite element simulation.

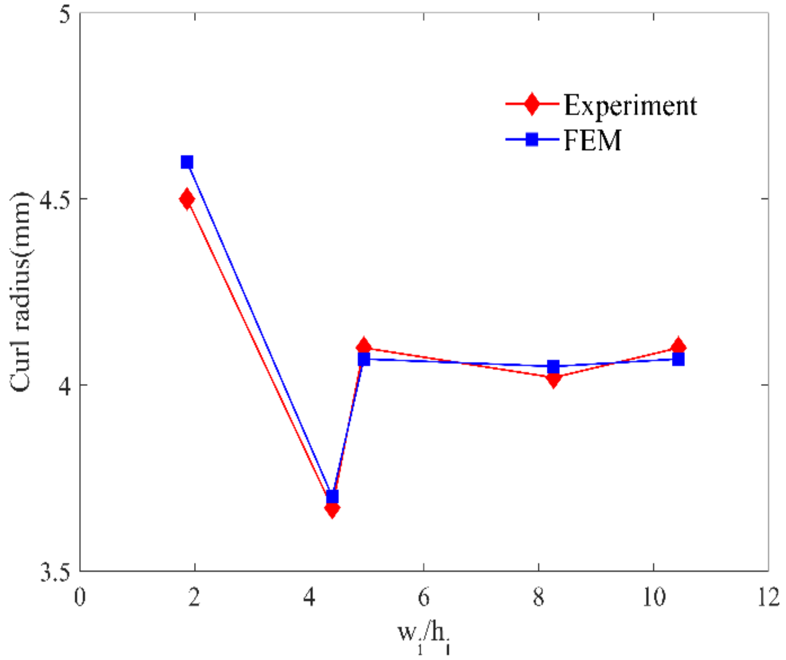


Figure 9. Effect of ratio of initial width to initial thickness of the sheet on the curvature radius of the output sheet for a thickness reduction percentage of 15%

Figure 10 shows the effect of the ratio of the initial width of the sheet to the initial thickness of the sheet on the final width of the output sheet. In this figure, the results of the output sheet width of the experimental results and the finite element simulation are compared. The findings show that there is a very high agreement between the two methods.

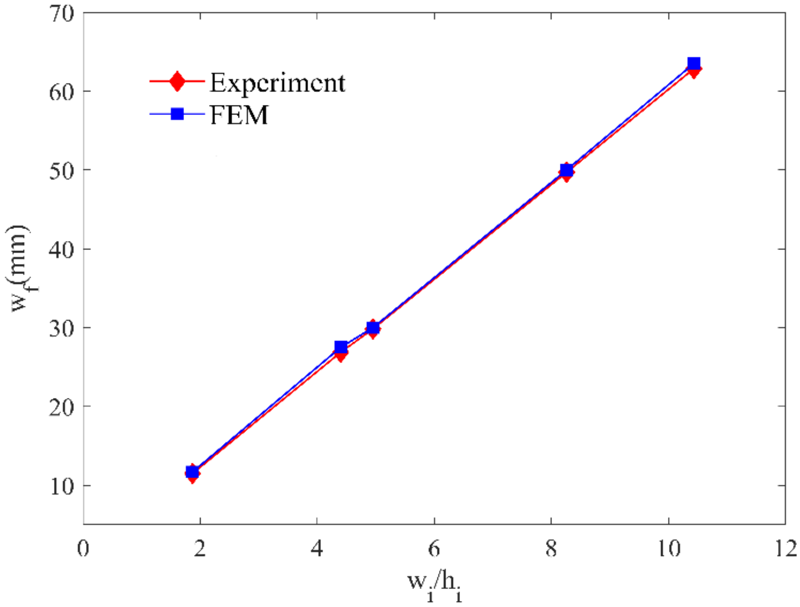


Figure 10. Effect of ratio of initial width to initial thickness of the sheet on the width of the output sheet for a thickness reduction percentage of 15%

For further study, a comparison between the experimental and simulation findings was made for a thickness reduction percentage of 20%. Figures 11 and 12 show the effect of the ratio of the initial width to the initial thickness of the sheet on the radius of curvature of the output sheet and the final width of the sheet, respectively. According to Figs. 9 and 11, it is clear that there is a good agreement between the simulation results and the experimental measurements and, as expected, the results of the finite element method do not completely match the experimental findings. The assumptions of rigid rolls and the challenges in simulating the friction at the contact surface between the sheet and the rolls may be the reason for these differences.

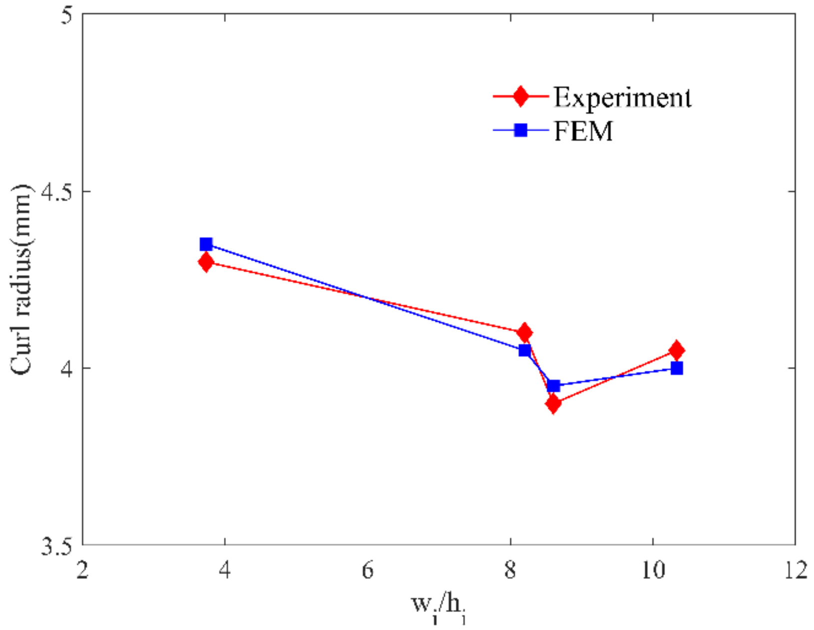


Figure 11. Effect of ratio of initial width to initial thickness of the sheet on the curvature radius of the output sheet for a thickness reduction percentage of 20%

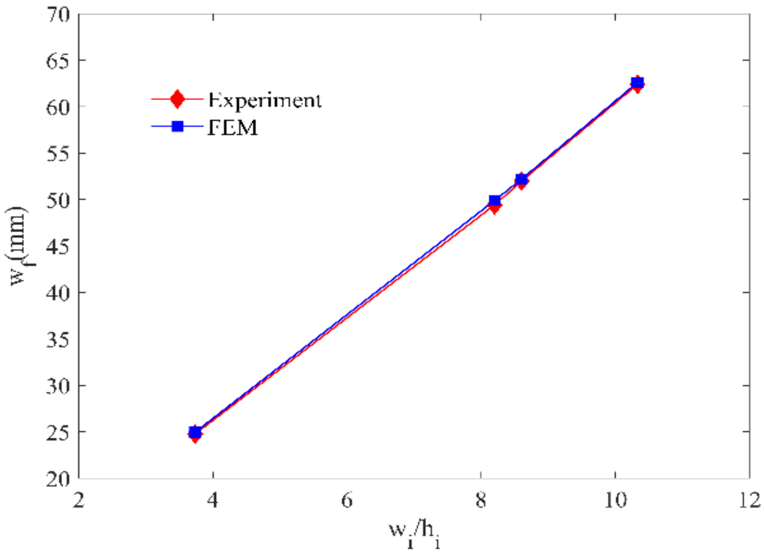


Figure 12. Effect of ratio of initial width to initial thickness of the sheet on the width of the output sheet for a thickness reduction percentage of 20%

5. Conclusions

In this paper, the three-dimensional asymmetric rolling process of metal sheets was investigated using experimental methods and finite element simulation. Using DEFORM 3D software, for pure aluminum sheets with initial width to initial thickness ratios of 2, 4, 6, 8 and 10, the output sheet width and radius of curvature were determined and compared with the results obtained from the experiment. The results obtained are as follows:

1. A good agreement was observed between the results obtained from the experimental method and finite element simulation.
2. By increasing the ratio of the initial width of the sheet to the initial thickness of the sheet, the curvature radius remains constant.
3. By increasing the ratio of the initial width of the sheet to the initial thickness of the sheet, the width of the output sheet increases.
4. By increasing the percentage of thickness reduction, the radius of curvature decreases from 15% to 20% and the width of the output sheet increases.

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