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Experimental and numerical analysis of the asymmetric flat rolling process of square section bars

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ABSTRACT

This paper analyzed the asymmetric flat rolling process of square section bars by testing experiments and finite element simulation methods. The impacts of the rate of roll diameter, decrease in altitude, and rotational speeds of the rolls on the width of cross-section and the curl radii at the leaving point of deformation for the brass and aluminum bar materials were investigated. Furthermore, the asymmetric rolling process of square section bars was simulated using ABAQUS commercial software. A great convergence was demonstrated among the findings forecasted by the FEM simulation and the experimental findings. It was found that by increasing the rate of rolling diameter, the curl radius and the width of the bar cross-section at the exit have been increased, and the roll speed has a insignificant impact on the width and the curl radius of the rolled bar.

Keywords: Asymmetric rolling; square section bar; experiment; curl radius.

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1. Introduction

Flat rolling is a metal forming procedure where cross-section dimensions of the metal sheets, wires, or bars are changed by passing through a pair of rotating cylindrical rolls with axes parallel to one another. The asymmetric term is utilized when the lower and the upper roll diameters, rotational speeds, or both are various. The asymmetric flat rolling process of a square bar is utilized in industry to create a bar of rectangular cross-section. Within this procedure, a square section bar is cold rolled among flat rolls to obtain the desired combination of height and width. The rectangular cross-section bars are utilized in various industries, including furniture and construction. They are also utilized to make products, including saw blades, coil springs, piston rings, and electrodes for gas metal arc welding [1]. Since the deformed bar is a semi-manufacture, it could be vital to forecast and control the width and curl radius to obtain the desired rectangular section rod dimension. A significant difference may be seen when the square section bar and sheet rolling were compared. It is common to assume a plane strain situation during sheet rolling; thus, the sheet's lateral dissemination may be disregarded. When the width spread cannot be ignored, rolling deformations are three-dimensional. The curl radius of the rolled bar, which is often seen as a process flaw, must also be taken into consideration in the asymmetrical rolling process, similar to the asymmetrical sheet rolling. Two design characteristics that precisely establish the geometric characterization of the finished product-the width of the rectangular cross-section and the curvature of the rolled bar-should be studied to allow control over them. An example of a valuable result from this procedure would be the curl radius, which may be used to create piston rings and torsional or helical springs, among other things.
In the past, many research were devoted to analyzing the parameters of asymmetric rolling process like the torque and the mill pressure, curvature and shape of the rolled sheet, by assay models [2-4] or finite element modelling [5, 6]. Ghobrial [7] employed the methodology of photo-elasticity and an experimental approach to

calculate touch pressures throughout plan strain asymmetric rolling process. He assumed that asymmetry caused by variation in roll radii had no major impact on the scale of the cross-section shear field. Hwang et al. [8] suggested an empirical model for asymmetric cold rolling of sheet, utilising the stream function principle and the upper bound theorem to examine the plastic behaviour of the sheet at the roll gap. Additionally tests on asymmetric rolling process have also been performed on aluminium, iron and steel. Hwang and Tzou [9], also having conducted analytical simulation and experimental studies of asymmetric rolling process, created an asymmetric rolling process model using the slab form, which assumes friction that is constant shear among the sheet and rolls. Tzou [10] explored the interaction among the Tresca and Coulomb friction coefficients. Furthermore, the impact of rolling constraints on this partnership was studied. Lu et al. [11] used the FE simulation technique to investigate the effect of different roll diameter ratio on sheet curvature. Liang et al. [12] investigated the asymmetrical sheet rolling process, in plan strain condition, using the finite element method. They discovered that there is an ideal ratio for the rolls' radii that results in flat sheets at the exit. Farhat-Nia et al. [13] used an ALE technique to mimic asymmetrical plate rolling while neglecting the lateral spread of the plate. They demonstrated that their technique accurately predicts the plate curvature. Parvizi et al. [14] investigated employing physical testing, finite element simulation, and certain theoretical formulas to simulate the asymmetrical wire rolling. They looked examined how a rolled wire's curvature radius and contact area were affected by roll speed ratio, roll diameter ratio, and height decrease. Yekta et al. [15] used a two-dimensional finite element (FE) model with an adaptive meshing approach to simulate the sheet asymmetric rolling process. Investigated were the impacts of the roll diameter to velocity ratio on the rolling force, rolling torque, and sheet curvature. A recent literature overview on the use of asymmetric rolling procedures for finite element analysis was published by Graca and Vincze [16].
The asymmetric flat rolling of square section bars has not yet been researched, even though a number of scholars have looked into the asymmetrical sheet rolling process. This study used experimental and numerical modeling approaches to study the asymmetric rolling process of square section bars. The asymmetric rolling test device was created and constructed specifically for asymmetric rolling experiments. In this inquiry, the asymmetric rolling of a square sectional bar has been examined for the first time utilizing empirical and FEM modeling approaches. Brass and aluminum have been used as test materials for square section bars. The studies have been carried out at the standard institute using the tensile experiments for aluminum and brass material to detect the precise true stress-strain behavior. The impacts of the roll diameter percentage and decrease in height on the bar curvature have been studied for both brass and aluminum bars. Additionally, researchers have looked at the impact of roll speed, the roll diameter rate, and the decrease in height regarding the width of the rolled bar cross-section. The simulation of asymmetric flat rolling of square section bars is done utilizing ABAQUS commercial software.

2. Experiments

The asymmetrical rolling of a square section bar is illustrated in Figure 1. The material starts as a straight square section bar and is rolled through a pair of parallel cylindrical rolls into a rectangular section curved bar. This figure shows the radii of the up and down roll R_1 around R_2, respectively. The rolls rotate with the angular velocities ω_1 and ω_2 as demonstrated in Figure 1. The asymmetric rolling process is assumed as a free procedure and the feeding load at the start of the process is neglected.

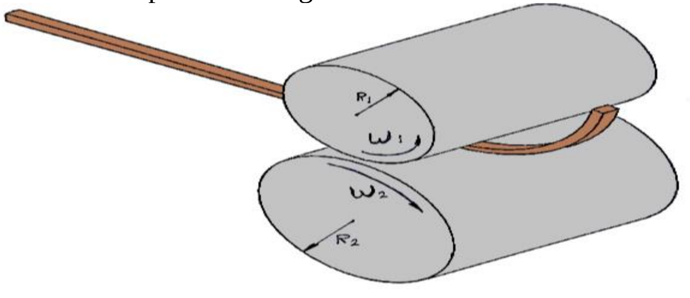


Figure 1. The asymmetric rolling process of a square section bar to a curved bar of rectangular section

The asymmetric flat rolling machine utilized in the experimental investigation has been designed and manufactured by the authors of this paper, as demonstrated in Figure 2. The rolling machine is powered by a single-phase electric motor with a capacity of 2.2 kW at rotational speeding of 1440 rpm and equipped with a gearbox to reduce the rotational speeding to 4 to 100 rpm. The asymmetric rolling machine consists of two stepped rolls. Utilizing these rolls, two ratios of roll diameter equal to Rdr1=1.666 and Rdr2=1.285 have been deemed for the tests. Furthermore, four various decreases in height are equivalent to 15, 20, 25, and 30% and three rotational speeds of 5, 10, and 15 rpm have been planned to carry out the rolling tests. Both the lower and upper rolls in the machine have been rotated with the exact rotational speeds, i.e. $\omega_1 = \omega_2$, A total number of 30 experiments have been carried out in such investigation. Certain tests have been repeated to arrive at more reliable findings. This investigation used aluminum and brass as bar materials for tests. The chemical compositions of the aluminum and brass bars are demonstrated in Tables 1 and 2.

Figure 2. Asymmetric flat rolling machine with two various roll diameter ratios.

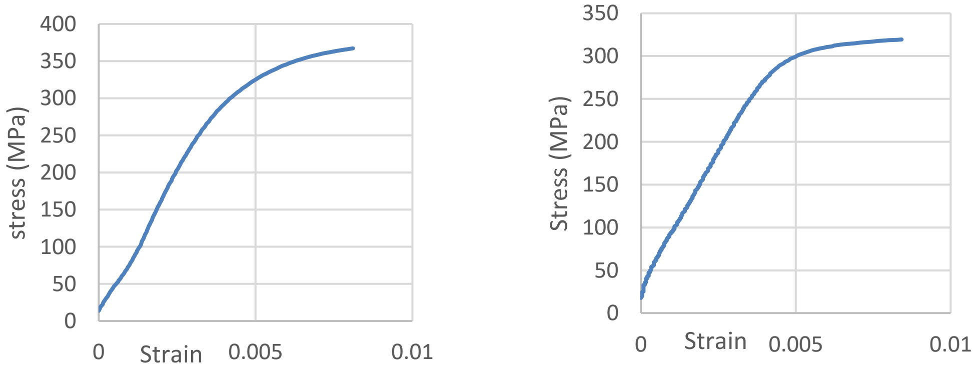
Table 1 Chemical analysis of the aluminum specimen

Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Ti	Be	Ca	Li
0.30	1.45	0.87	0.56	1.9	0.03	0.03	3.15	0.014	Trace	Trace	Trace
Pb	Sn	Sr	V	Na	Bi	Co	Zr	B	Ga	Cd	Al
0.30	<0.005	Trace	0.011	Trace	0.005	0.006	Trace	0.0055	0.008	0.007	Base

Table 2 Chemical analysis of the brass specimen

Zn	Pb	Sn	P	Mn	Fe	Ni	Si	Cr	Al	S
38.24	1.7	0.22	0.01	Trace	0.50	0.15	<0.005	Trace	0.06	0.008
Ag	Co	Cu								
0.01	<0.01	59.10								

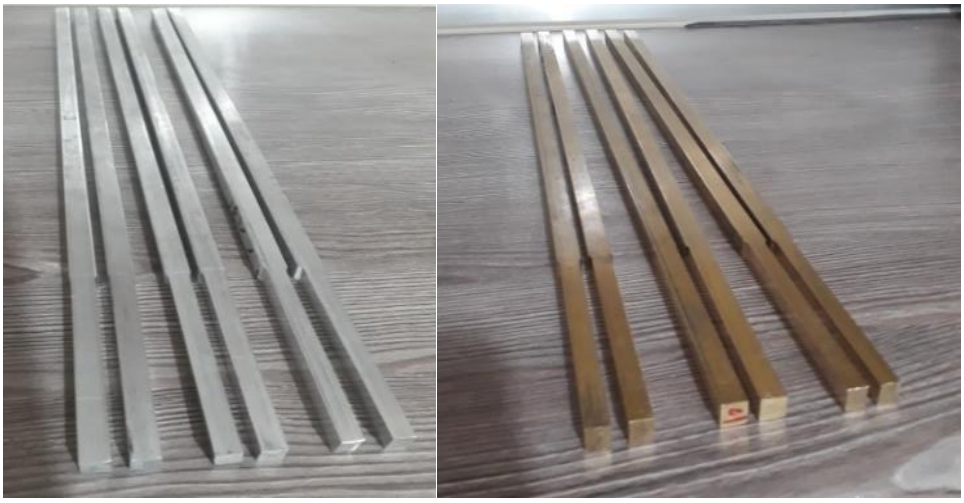
In order to get the stress-strain curves of the materials at room temperature, the tensile tests have been performed in the typical manner to identify the precise, true stress-strain curves. The standard institute performed tensile testing on the brass and aluminum bars used in the trials to produce the precise real stress-strain curves seen in Figure 3. In order to obtain the stress-strain curve of materials at room temperature, tensile test pieces were also made from aluminum and brass materials. The tensile experiment was conducted at room temperature at a ram speed of 0.5mm/min. The true stress-true strain curves obtained for the materials are shown in Figure 3.



(a) brass (b) aluminum

Figure 3. True stress–strain curves brass and aluminum materials.

The aluminum and brass specimens had a square section of 6*6 mm, which is demonstrated in Figure 4. The square section bars are machined to the dimension 500 mm in length and have been cleaned with carbon tetrachloride before rolling. The aluminum and brass bars after the asymmetric rolling process are illustrated in Figure 5.



(a) Aluminium square section bars (b) Brass square section bars

Figure 4. Aluminium and brass square section bars

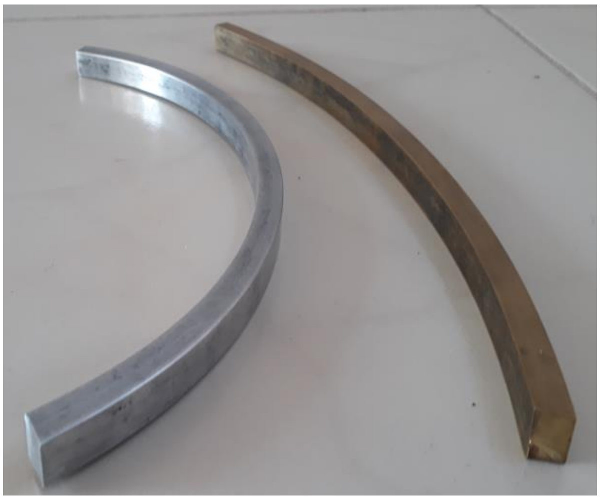


Figure 5. The aluminum and brass bars after the asymmetric rolling process

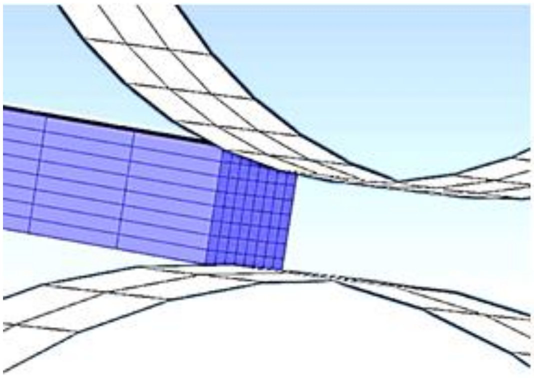
3. Finite element simulation

In this investigation, the FE analysis software ABAQUS was utilized to simulate square section bars' asymmetric flat rolling process. A 3-dimensional model is utilized for FEM investigation. The material characteristics of the brass and aluminum square bars are mentioned in Table 3 and have been utilized in the finite element simulation.

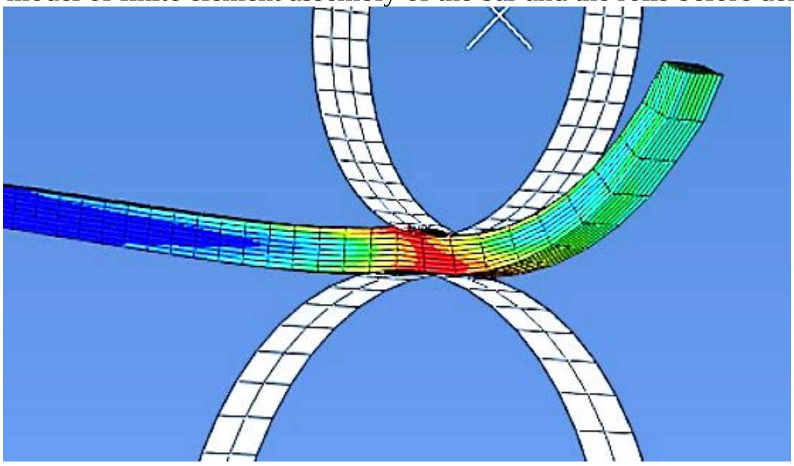
Table 3 Mechanical properties of the brass and aluminum bars

Bar material	Density (kg/m^3)	Yield Stress (MPa) 0.2% offset	Modulus of elasticity (GPa)	Poisson's proportion
Brass	8500	367	81	0.32
Aluminum	2710	319	63	0.33

The rolls have been 3D analytic rigid shells, whereas the bar was modelled as a solid extruded and solid homogeneous. The bar meshed with 16900 elements and the C3D8R element type. The mesh sensitivity was utilized to authorize the appropriation of the number of components. Increasing the number of elements does not significantly impact the obtained findings. The friction coefficient between the roll and bar was estimated to be 0.3, similar to the requirements for dry friction; the friction coefficient at the lower and upper rolls is assumed to be the same. Top and bottom rolls have the same roll speeding. Figure 6a illustrates the bar's 3D finite element model assembly and the rolls before deformations. The deformed mesh is demonstrated in Figure 6b.



(a) 3D model of finite element assembly of the bar and the rolls before deformations



(b) Bar after deformations and distribution of effective stress

Figure 6. Simulation of the asymmetric rolling of the square section bar to rectangular section bar

4. Results And discussion

The impact of the decrease in altitude on the curl radius of the square section brass bar for two ratios of roll diameter is demonstrated in Figure 7. From this Figure , it could be noticed that when decrease grows, the curl radius decreases. This Figure also demonstrates that the curl radius rises with the growth in the roll diameter ratio.

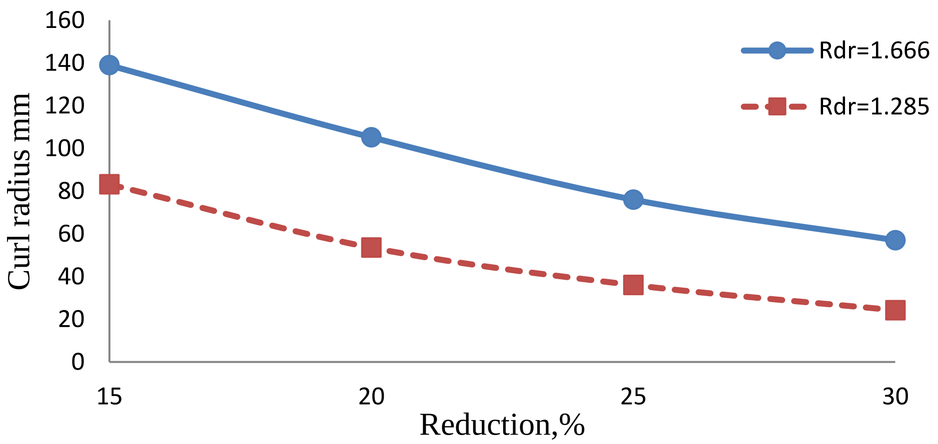


Figure 7. The impact of the percentage decrease in altitude on the curl radii of the brass bar for two ratios of roll diameter at roll speeding 5 rpm.

Figure 8 illustrates the impact of the decrease in altitude on the radii of the aluminum rod at the leaving point of the deformations area for 2 ratios of roll diameter. The findings illustrate that once the decrease in height grows, the rod radius at the leaving point decreases. The comparison of measured curl radii as a function of the percentage of reduction is demonstrated in Figs. 7-8 demonstrate that the curl radii of aluminum bars are smaller than those of the brass bars.

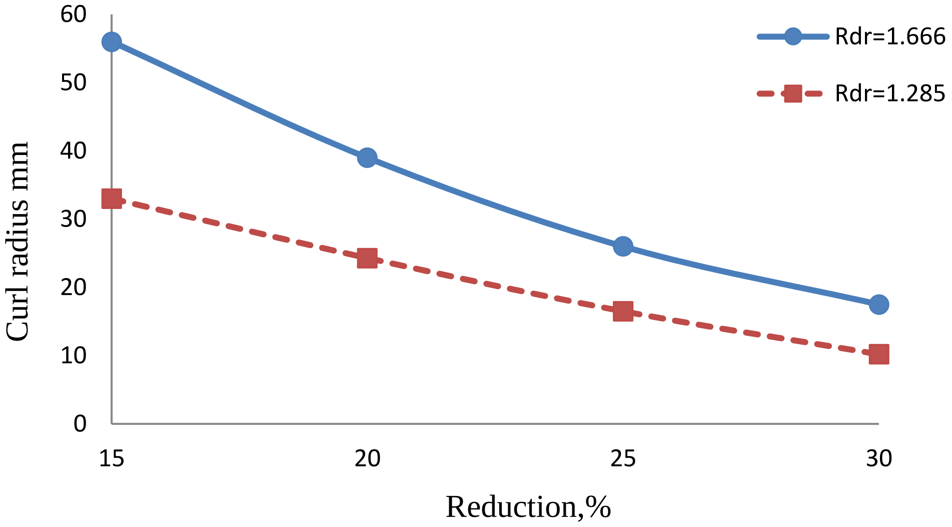


Figure 8. The impact of the decrease in altitude on the curl radius for the aluminum bar for two ratios of roll diameter at roll speeding 5 rpm.

For comparison, the corresponding findings are also obtained utilizing the FE simulation. The comparison between the experimental and simulation findings for the curl radius as a function of the percentage reduction in height is demonstrated in Figure 9. It was detected that a good agreement exists between simulated findings and the experimental measurements. As expected, the FE data are always smaller than the experimental findings. The assumptions of rigid rollers and the challenges in simulating friction in the contacting surface between the deforming rod and rolls might be blamed for these differences. It could be detected from Figure 9 that widths increase with the increase in reduction. Comparing the experimental findings and FE findings demonstrated in Figure 9, the error is about 6%.

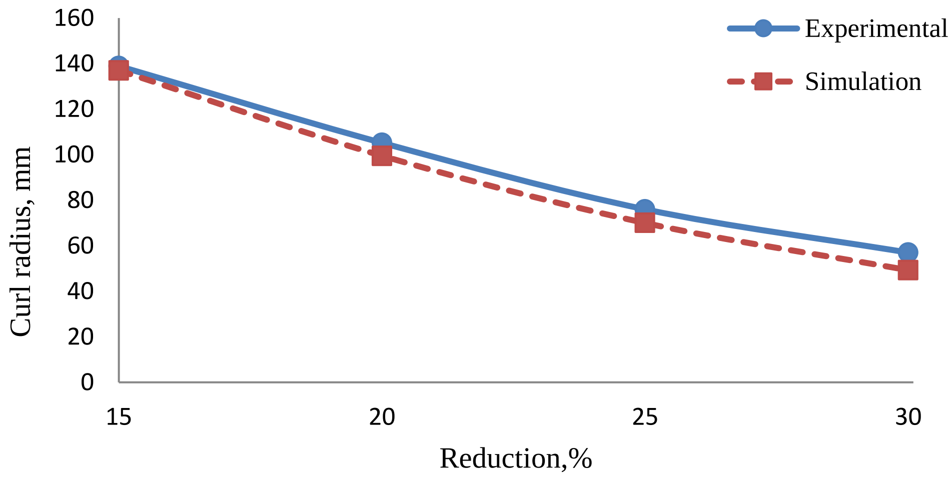


Figure 9 Comparison of the measured curl radii with the FE simulation data for the brass bar, the ratio of roll diameter 1.666 and roll speeding 7 rpm.

The decrease in height impact on the cross-section width at the exit for the brass and aluminum bar materials is illustrated in Figure 10. It could be observed that the cross-section width is increased with the increase of the percentage of reduction in height. Figure 9 shows that the width of the cross-section at the exit of the deformations area is increased by increasing the ratio of roll diameter. Additionally, the percentage of increase is greater for the larger capacities of decrease in altitude.

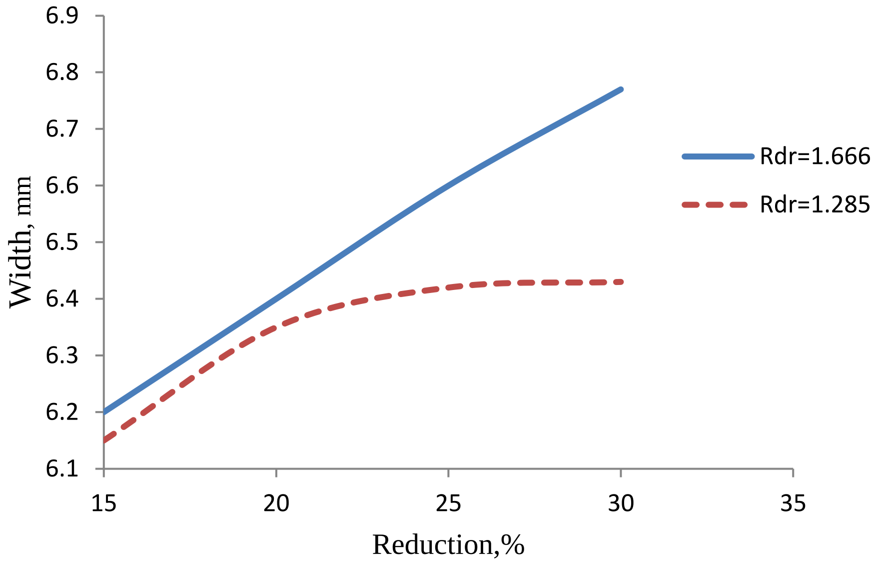


Figure 10. The impact of reduction on the width of the cross-section at the exit for brass bar.

The comparison between the experimental findings and FEM simulation magnitudes for the width of the cross-section at the exit as a function of the percentage reduction in height is demonstrated in Figure 11. It is observed that the FE data are basically in agreement with the measured ones. As expected, the FE data are always greater than the experimental findings. Such discrepancies may be attributed to simplifying the meshing and FE simulation. It can be checked from Figure 11 that widths increase with the increase in reduction. Comparing the experimental findings and FE findings demonstrated in Figure 10, the error is about 8%.

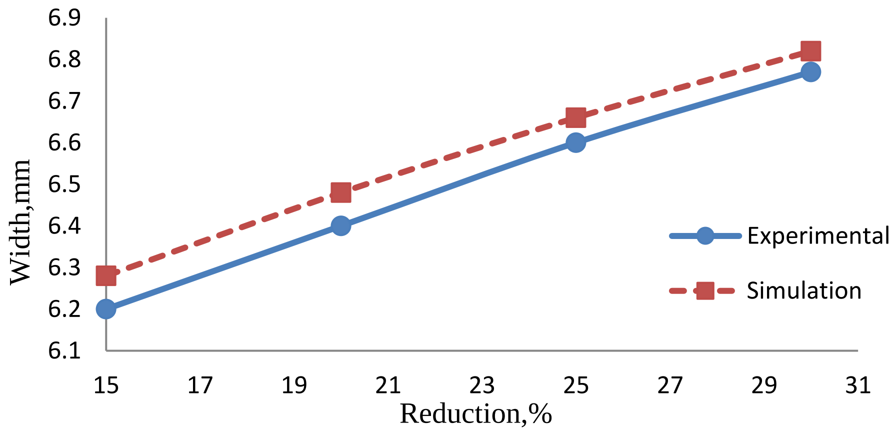


Figure 11. The comparison between the experimental and the FE data of the width of the cross-section at the exit (roll diameter ratio 1.666, rotational speeding of 7 rpm).

The impact of the roll speeding upon the curl radii and the width of the cross-section of the rolled bar for the brass bars are illustrated in Figs. 12 and 13, respectively. From these Figure s, it is known that the impact of roll speeding upon the curl radius and the width of the bar cross-section at the exit of the deformations area is negligible.

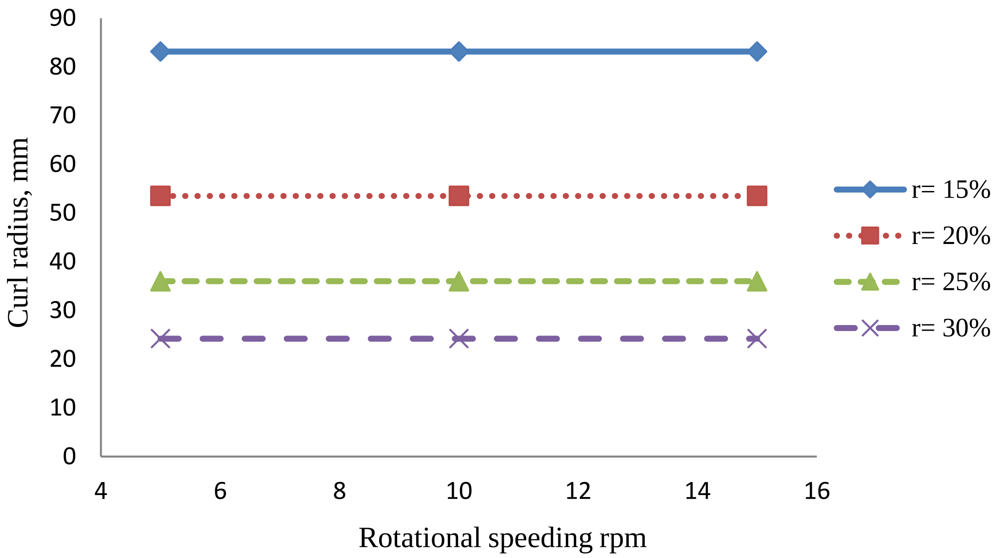


Figure 12. The impact of the roll speeding on the curl radii of the rolled brass bar

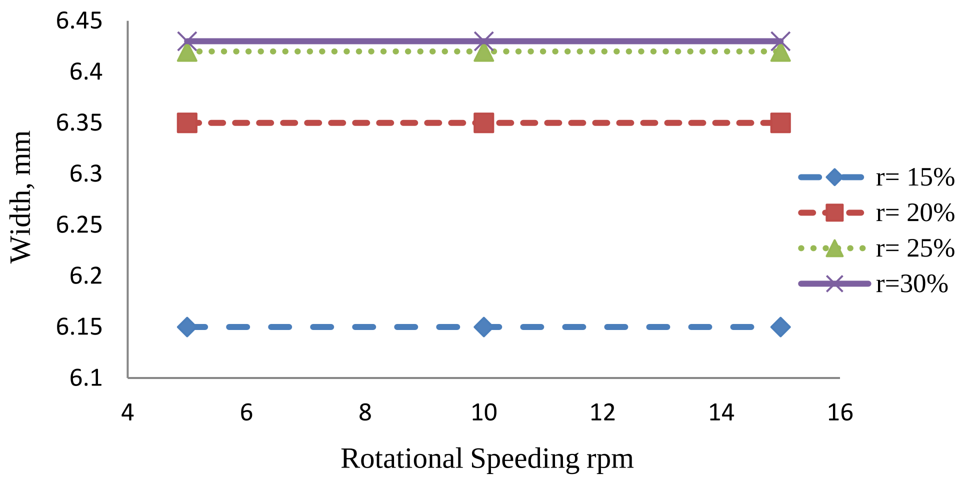


Figure 13. The impact of the roll speeding on the section width at the exit for the brass bar

5. Conclusions

In this research investigation, the asymmetric flat rolling process of the square section bars was investigated experimentally and FEM simulation methods. The impacts of the ratios of roll diameter, roll speeding and the decrease in altitude was investigated on the curl radii and the cross-section width of the rolled rod. Through the analysis, the following items have been concluded:

- By increasing the rate of diameter roll, the curl radii and the width of the bar cross-section at the exit were increased.
- By increasing the decrease in altitude, the curl radii was decreased and the width of the bar cross-section at the exit was increased.
- The curl radius and the width of the bar cross-section at the exit of aluminum bars were lower than those of the brass bars.
- The findings demonstrated that the roll speed had no impact on the curl radius and width of the roll bar cross-section.
- Results from experimental measurements and those from finite element modelling have a fair degree of agreement.

Declaration of competing interest

The authors declare that they have no any known financial or non-financial competing interests in any material discussed in this paper.

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