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Technical Paper

Analysis of curvature and width of the contact area in asymmetrical rolling of wire

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ABSTRACT

In this paper, an investigation into the asymmetrical wire rolling is presented using experimental tests, finite element simulation, and some analytical formulations. Moreover, the effects of the roll speed ratio, roll diameter ratio, and reduction in height on the curvature radius, and width of the contact area of a rolled wire are investigated. In addition, possibility of applying a theoretical formula for calculating the width of the contact area in the symmetrical wire rolling for the asymmetrical wire rolling is also studied. A very good agreement is shown to exist between the results predicted by the FEM simulation and the experimental results.

1. Introduction

In the wire rolling, the wire is contoured between two rolls gap to achieve the desired thickness. Asymmetrical rolling, as shown in Fig. 1, is when the initial material for wire rolling is of a circular cross section and the final product is a flat wire with rounded edges on both sides. The wire manufactured from wire rolling process mostly used in the production of the electrical equipment, piston rings, saw blades, springs, and flat-wire electrode for gas metal arc welding (GMAW) [1].

When comparing the asymmetrical with the symmetrical process, the radii, speeds, and surface roughness of the working rolls may be dissimilar. One advantage of asymmetrical rolling is that the rolling force and torque can be decreased which saves the required energy to accomplish the process. In addition, asymmetrical wire rolling allows for the higher reductions within a single pass to be obtained.

In the past, some analytical and experimental methods are used by a small number of researchers to predict the final results of symmetrical wire rolling processes. Using theoretical and experimental methods, Kazeminezhad and Karimi Taheri [2] investigated the effects of the thickness reduction, roll speed, and wire material on the width of the contact area and lateral spread of wire. Their results showed that the roll speed and the wire material do not affect the width of the contact area and lateral spread, while these parameters are changed by the reduction in thickness. They also presented a relation between the variations of the thickness and width of the contact area. Using an experimental investigation, Kazeminezhad and Karimi Taheri [3] evaluated the effects of the friction coefficient, thickness reduction, and roll speed on the rolling force and deformation behavior. Their investigations showed that the roll speed has a considerable effect on the rolling force, but does not have an effect on the deformation behavior.

Using slab method analysis, Kazeminezhad and Karimi Taheri [4] also studied the effects of the thickness reduction, friction coefficient, and yield stress on the rolling pressure distribution, rolling force, and position of the natural point in the symmetrical wire rolling. Following their previous study, Kazeminezhad and Karimi Taheri [5] studied the deformation inhomogeneity in the flattened wire produced in the symmetrical wire rolling. They concluded that as the reduction in height decreases and friction factor increases, the deformation inhomogeneity in the wire increases as well.

Using the empirical and analytical formulae as well as the numerical methods, the cross-sectional profile of flattened wires after the flat rolling process was investigated by Kazeminezhad and Karimi Taheri [6]. Among the approaches, the numerical method is able to estimate the lateral spread, width of the contact area, and curvature radius in all ranges of the reduction in height with high degree of accuracy. Moreover, Kazeminezhad and Karimi Taheri

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Nomenclature

b	width of the contact area (mm)
d_1, d_2, d_3	different roll diameter ratios
d_u, d_l	diameter of upper and the lower work rolls, respectively (mm)
h_0	initial thickness of the wire (mm)
n_u n_l	angular velocities of the upper and the lower rolls, respectively (rpm)
V_1, V_2, V_3	different roll speed ratios
Δh	reduction in wire height (%)

[7] studied the effect of the 3D and 2D deformation on flattened wire. They predicted the effective strain fields in the flat rolled and side-pressed wires. They concluded that for both flat rolled and side-pressed wires, the strain inhomogeneity increases with increasing the height-to-width ratio and friction factor. Kazeminezhad and Karimi Taheri [8] used the combined Finite and Slab Element Method (FSEM) to investigate the creation of the macroscopic shear bands. In order to verify the FSEM method, they carried out a Vickers micro hardness measurement and showed the minimum and maximum effective strain at the round edge and center of the flattened wire.

In addition to the theoretical and experimental analysis, finite element method is also utilized by some researchers to analyze the symmetrical wire flat rolling process. Carlsson [1] simulated the wire flat rolling process for evaluating the pressure distribution. It was concluded that the maximum pressure happens at the entrance. Iankov [9] estimated the effects of the friction, back, and front tension on the contact pressure distribution and lateral spread in the symmetrical wire flat rolling process. He concluded that due to the inhomogeneous deformation, the shear bands appear in the cross section of the flattened wire. Vallellano et al. [10] investigated the contact stress distribution and residual stress in the rolling of wire by 3D finite element method. They found that there is a maximum contact pressure in the roll entry zone due to the strong local inhomogeneity of deformation.

After comparison between rolling of wire and sheet, a major dissimilarity is noticeable. In fact, it is typical to suppose a plane strain condition in the sheet rolling; hence the lateral spread of sheet could be neglected. However, in the wire rolling process, the lateral spread cannot be ignored. Furthermore, similar to the asymmetrical sheet rolling, the radius of formed wire at exit should also be considered in the asymmetrical wire rolling process. Since the width of contact area and the radius of the rolled wire at exit are two design parameters which define the geometry characterization of the product, they should be investigated specifically to enable to control them. For instance, the outgoing curvature, which is commonly considered as an imperfection of the asymmetrical rolling process, could be regarded as a useful output of this process, while it may be used to produce torsional or helical springs, etc. Having explored the literatures, no researcher has presented an article investigating the width of wire in the contact area and radius of flat wire at exit in the asymmetrical wire rolling. However, there are just some studies focused on the analyses of sheet curvature in the asymmetrical rolling process.

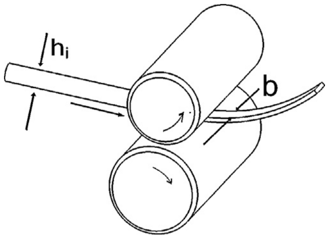

Fig. 1. Asymmetrical wire rolling process.

Table 1
Stress-strain behavior of copper and brass.

Copper					
Strain	0.002	0.11	0.13	0.15	0.17
Stress (MPa)	330	350	390	414	420
Brass					
strain	0.002	0.08	0.24	0.5	0.8
Stress (MPa)	130	156	182	208	239

The first research about the asymmetrical sheet rolling was almost done by Sachs and Klinger [11]. They found that there is a region in the deformation zone where the friction forces act in the opposite direction and make sheet to bend at the exit plane. Richelsen [12] used an elastic–plastic finite element method to analyze the effect of the friction ratio on the curvature of the sheet at exit of the deformation zone. He found that the direction of the curvature of sheet is toward the roll with higher friction. Salimi and Sassani [13] presented a relation for calculating the curvature of the rolled plate at the exit of the deformation zone.

Lu et al. [14] estimated the effect of the different roll diameter ratios on sheet curvature at exit using finite element simulation. Liang et al. [15] used a finite element method to study the asymmetrical sheet rolling. They found that there is an optimum rolls radii ratio that produce flat sheet. Farhat-Nia et al. [16] simulated the asymmetrical plate rolling using an ALE approach. They proved that their ALE method predicts the sheet curvature at exit of the deformation zone with a good accuracy.

Although a number of researchers have studied the symmetrical wire flat rolling process, no investigation has been studied about the asymmetrical wire flat rolling process until now. Using an experimental and FEM simulation methods, the asymmetrical wire rolling is investigated for the first time in this study. The effects of the reduction in height and roll diameter ratio on the wire curvature for both copper and brass wires are studied. Moreover, the effects of the roll speed ratio, roll diameter ratio, and reduction in height on width of the contact area are investigated for both wires. Using ABAQUS explicit, the asymmetrical wire rolling is simulated in all aspects. Furthermore, accuracy of applying a theoretical formula, which was presented to calculate the width of wire in the symmetrical wire rolling for the asymmetrical process is also investigated. Finally, it is shown that there is good agreement between results from experimental study and those from finite element simulation.

2. Experiments

In Fig. 2, the roll mill and three sets of rolls used in the experimental study are shown. Mill consisted of two rolls driven by an electric power pack. The rolls were made of steel CK60. Six main rolls with diameters equal to 73, 69, 64.4, 53.6, 49, and 45 mm were fabricated. Using these rolls, three roll diameter ratios equal to $d_1 = 64.4/53.6 = 1.2$, $d_2 = 69/49 = 1.4$, and $d_3 = 73/45 = 1.6$ were considered for the asymmetrical experiments. Moreover, four different reductions in height equal to 13, 22, 30, and 45% were planned to perform the experiments. Both the upper and the lower rolls in the mill were rotated with the same rotational speed. A total number of 24 experiments were performed in this study. Some experiments were replicated to achieve the more reliable results.

In this study, copper and brass were used as materials of wires for tests. The tensile tests for the copper and brass wires used in the experiments were carried out in the standard institute to determine the accurate stress-strain behavior which is shown in Table 1.