

Article

Influence of Roll Diameter on Material Deformation and Properties during Wire Flat Rolling

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Abstract: The influence of roll diameter on the strain distribution, shape change, contact pressure, and damage value of a workpiece was investigated during wire flat rolling to control the material properties of the flattened wire. The flattened wires fabricated by the four different rolls were compared using finite element analysis. The strain inhomogeneity of the flat-rolled wire increased with the roll diameter; thus, the macroscopic shear bands were strengthened as the roll diameter increased during wire flat rolling. The contact width and lateral spreading of the flattened wire increased with the roll diameter; therefore, the reduction in area decreased with the roll diameter. The contour of the normal contact pressure on the wire surface exhibited a similar pattern regardless of the roll diameter. The contact pressure showed higher values at the entry, edge, and exit zones in the contact area. The distribution of the damage value varied with the roll diameter. The free surface region tended to have the peak damage value during the process; however, the center region exhibited the maximum damage value with the roll diameter. From the perspective of the damage value, the optimum roll diameter was in existence during wire flat rolling. The underlying cause of the different strain distributions, shape changes, and damage values of the flat-rolled wire was the different contact lengths originating from the different roll diameters during wire flat rolling.

Keywords: roll diameter; wire flat rolling; strain distribution; contact pressure; damage value



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1. Introduction

Wire flat rolling is the process of reducing the height of a round wire by passing it through two counter-rotating flat rolls. Despite the use of flat rolls, the deformation behavior of a workpiece is relatively complex during wire flat rolling because a round wire is used as the initial workpiece, which is different from the strip or plate flat rolling. The issue of strain inhomogeneity in a flat-rolled wire is inevitable because stress is concentrated in the central regions of the wire owing to the geometric forming and loading conditions during the process [1]. The more essential reason is that the wire flat rolling process belongs to the compression-type cold forming process. The strain inhomogeneity in the compression-type forming processes is attributed to the restricted metal flow in the workpiece and die interface owing to the resistant shear stress generated by friction. In this manner, macroscopic shear bands (MSBs) commonly occur during compression-type forming [2,3]. Meanwhile, the issue of strain inhomogeneity of the flattened wire is becoming critical because the demand for nonheat-treated products increases continuously from metal forming and its downstream industries. In addition, the elimination of heat treatments is a major trend in the metal manufacturing industry to reduce production costs, production cycles, and greenhouse gas emissions. For instance, Hwang [4,5] recommended twinning-induced plasticity (TWIP) steel as an innovative metal for use in high-performance flattened wire products. He suggested the use of TWIP steel as flat-rolled wire products without the application of any heat treatments during the entire manufacturing process owing to its

high ductility as well as high strength [6,7]; this is highly advantageous from the manufacturer's perspective. However, these studies revealed that strain inhomogeneity occurred in the flat-rolled wire, indicating the necessity of heat treatments during the manufacturing process to reduce the strain inhomogeneity of the flattened wire. This is not the preferred direction for manufacturing processes in metal forming and related industries [8,9].

Therefore, considerable efforts have been expended to predict and decrease the strain inhomogeneity of flattened wires during the process using experimental and numerical approaches. It has been revealed that the strain distribution of the flat-rolled wire depends significantly on the working conditions, such as lubrication, reduction ratio, roll diameter (D), and rolling speed [1,5,10–12]. According to the previous studies, the homogeneity of the mechanical properties increased with a decreasing friction coefficient and roll diameter, and with an increasing reduction ratio. It was reported that the influence of the rolling speed on strain inhomogeneity is insignificant. Although the roll diameter is a working condition that can be changed easily in industrial fields, only a few investigations have focused on the effect of the roll diameter on the wire quality during wire flat rolling. For example, Hwang [5] reported that the strain homogeneity of the flat-rolled wire increased with decreasing roll diameter; however, only the results were reported, and the detailed underlying mechanism was not revealed in the study.

Meanwhile, the shape control of the product is crucial in metal forming processes. In particular, the fabrication of the desired product shape is more important in the rolling process because direct control of the product shape is impossible during the process originating from the spreading effect at the free surface of the workpiece [13–17]. During wire flat rolling, spreading occurs more easily compared with plate or strip flat rolling because of the initial shape of the wire with a high width to height ratio [18,19]. From an industrial perspective, it is challenging for engineers to overcome the issue of shape control because the shape of the rolled product varies with both the working conditions and material properties. Therefore, the shape change behavior of a workpiece during wire flat rolling with the roll diameter must be understood.

Hence, this study mainly focuses on the influence of roll diameter on the deformation behaviors, such as the strain distribution, shape change, contact pressure, and damage value of the workpiece during wire flat rolling to control the material deformation and properties of the wire. For a systematic comparison study, flat-rolled wires fabricated using the four different rolls were compared using finite element (FE) analysis.

2. FE Analysis and Model Validation

2.1. FE Analysis and Boundary Conditions

During wire flat rolling, the workpiece exhibits three-dimensional (3D) deformation behavior owing to the initial round shaped wire [15]. Accordingly, FE analysis was conducted using the commercial software, DEFORM 3D version 11.0 (Scientific Forming Technologies Corporation, Columbus, OH, USA) to evaluate the deformation behavior of the workpiece during wire flat rolling.

The 13 mm-diameter wire was reduced to a 9.1 mm-thick flattened wire by flat rolls with diameters of 150, 400, 800, and 1600 mm at room temperature (RT, 24 °C), as schematically shown in Figure 1. Hereafter, the flat-rolled wires fabricated using rolls with diameter of 150, 400, 800, and 1600 mm are referred to as “150-wire”, “400-wire”, “800-wire”, and “1600-wire”, respectively. During the process, the reduction in height (R_h) and reduction in area (R_A) of the workpiece were calculated using the following equations:

$$R_h = \frac{h_0 - h_1}{h_0} \times 100 (\%) \quad (1)$$

$$R_A = \frac{A_0 - A_1}{A_0} \times 100 (\%) \quad (2)$$

where h_0 and h_1 represent the initial and final heights of the workpiece; and A_0 and A_1 indicate the initial and final areas of the workpiece, respectively. The nominal strain (ϵ_n) of the workpiece was calculated using the height of the workpiece as follows:

$$\epsilon_n = \ln \frac{h_0}{h_1} \quad (3)$$

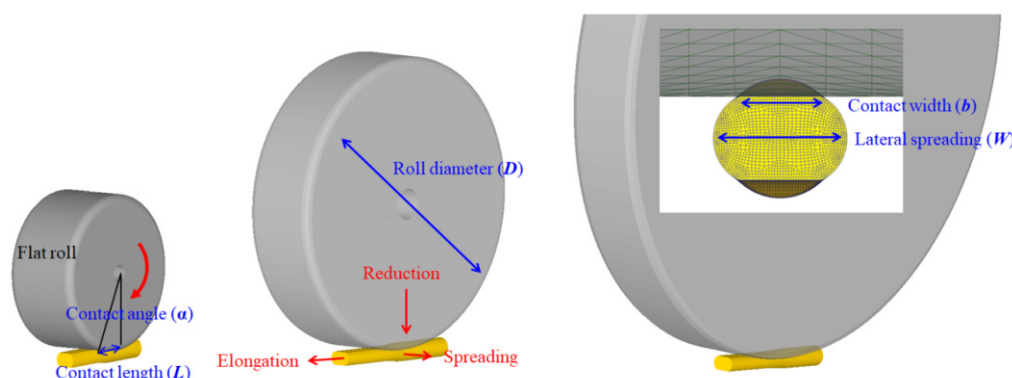


Figure 1. Schematic illustration of wire flat rolling with the roll diameter and related parameters used in this study.

According to the equations above, the R_h and ϵ_n values in the present study were 30% and 0.36, respectively.

Friction plays a crucial role in determining the deformation behavior of a workpiece during the rolling process because friction is the main reason for the rolling process to take place. Although a Tresca model (shear friction factor) is preferable in high-pressure bulk forming processes [20], the Coulomb friction model was applied at the roll and wire interfaces because it is known that the shear friction model cannot predict the sticking region near the neutral point during plate flat rolling [21]. Accordingly, in this study, the Coulomb friction model was applied as follows:

$$\tau = \mu p \quad (4)$$

where, τ , μ , and p are the frictional stress, coefficient of friction, and normal pressure, respectively. In the present study, a constant friction coefficient of 0.15 was used because Kazeminezhad and Karimi Taheri [22] well predicted the roll force during wire flat rolling using the friction coefficient of 0.17 although it is known that the friction coefficient in the roll bite varies with the rolling [23] and width [24] directions of the workpiece during rolling. In addition, the friction coefficient of 0.15 was a reasonable value for the cold rolling process without lubrication.

The influences of temperature increase and rolling speed were not considered during the process because the rolling velocity was set to 5 rpm, that is, a low strain rate or forming speed. The roll was considered to be a rigid body because the plastic deformation of the workpiece was relatively large, i.e., R_h of 30%. In such a case, the elastic deformation of roll can be ignored.

Owing to the double symmetry condition in both the reduction and spreading directions during wire flat rolling, only a quarter of the full geometry of both the wire and roll were modeled. Hence, a significant reduction in computational costs was achieved.

2.2. Experimental Procedures

Experimental tests were conducted to validate the present FE model. A 50 kg ingot with a chemical composition of Fe-19.94Mn-0.6C-1.03Al in weight percent was fabricated using a vacuum induction method under inert gas. After homogenization in a box furnace at 1200 °C for 12 h, the ingot with 125 mm in thickness was directly rolled to a 20 mm-thick plate in the temperature range of hot deformation in steels (from 950 °C to 1150 °C) using

several rolling machines. Subsequently, it was naturally cooled in air to RT in order to simulate the hot rod rolling process. Tensile specimens (5 mm-diameter and 25 mm-long in gauge) machined from the hot-rolled plate were pulled at a strain rate of 10^{-3} s^{-1} at RT. Figure 2a presents the true stress–strain curve of the hot-rolled steel. This steel exhibited high strength and excellent elongation owing to the deformation twinning during plastic deformation [6,7]. For a better evaluation of the strain hardening behavior of this steel, Holloman’s law was used to evaluate the strain hardening exponent (n) as follows:

$$\sigma = K\epsilon^n \quad (5)$$

where K is the strain hardening coefficient. Based on the above equation, the instantaneous n was calculated with true strain using the following equation:

$$n(\epsilon) = \left. \frac{d \ln \sigma}{d \ln \epsilon} \right|_{\dot{\epsilon}, T=\text{const.}} \quad (6)$$

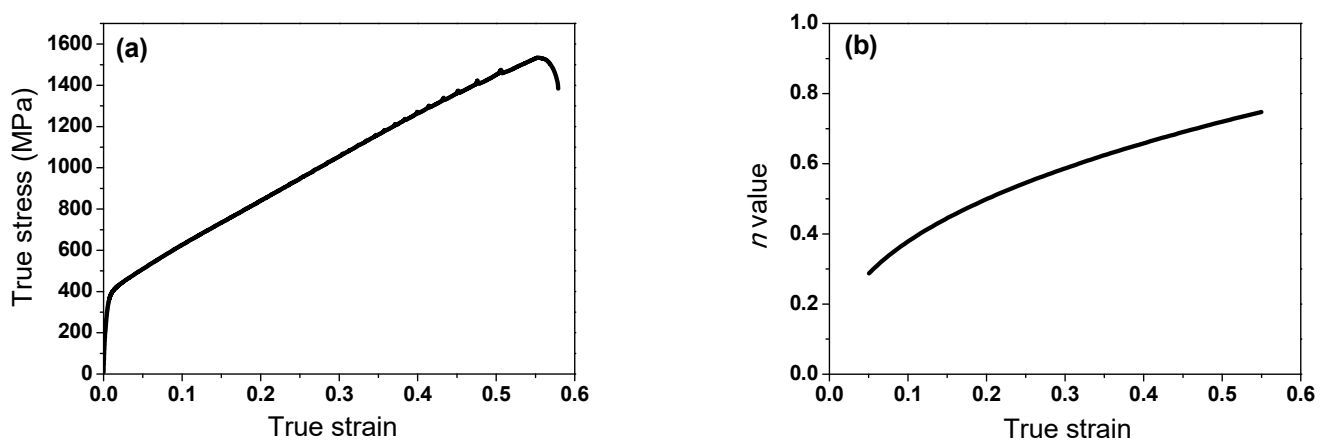


Figure 2. (a) True stress–strain curve and (b) calculated n of the hot-rolled TWIP steel.

The instantaneous n increased gradually with the true strain as shown in Figure 2b.

Several 13 mm-diameter wires were machined from the hot-rolled plate along the rolling direction. In addition, the initial wires were reduced at an R_h of 10%, 20%, 30%, and 40% using a single pass-type rolling simulator with 400 mm-diameter flat rolls at RT. No lubricant was applied to the wire prior to the wire flat rolling process. The rolling speed was set to 5 rpm to ignore the temperature rise or strain rate effects during the forming process.

2.3. Flow Stress Model

TWIP steel was used as the model material to simulate the wire flat rolling process. The workpiece was assumed to be a rigid-plastic material because the plastic deformation occurred primarily during rolling, and the elastic deformation was relatively small. Hence, the elastic deformation part is negligible. In addition, the workpiece was assumed to be an isotropic material with strain hardening effect. The strain rate effect was not considered owing to the cold forming process and the slow rolling velocity of 5 rpm. In such a case, Hollomon’s law in Equation (5) can describe the constitutive behavior of a workpiece. From the curve fitting of the stress–strain curve in the TWIP steel (Figure 2), K and n values were determined to be 1980 MPa and 0.54, respectively.

2.4. Convergence Analysis of FE Mesh

To determine the appropriate number of elements, the deformation behavior of the wire was evaluated with the number of elements at the roll diameter of 400 mm. The number of elements in the cross section of the wire was changed from 100 to 500, and

that in the longitudinal direction of the wire was fixed at 60. The shape change and strain distribution were used as the parameters for the convergence analysis of the FE model. Figure 3a shows the shape of the deformed flat-rolled wire and contour of the von Mises equivalent strain (effective strain) with the number of elements. Figure 3b compares the contact width (b) and lateral spreading (W), and Figure 3c shows the maximum effective strain (ϵ_{max}) of the flat-rolled wire against the number of elements. The values of b , W , and ϵ_{max} increased gradually with the number of elements. As expected, the difference in the variables between the two closest decreased with an increase in the number of elements. From an engineering perspective, the number of elements was selected as 300 because it adequately reflected the deformation behavior of the wire. Therefore, approximately 18,000 only hexahedral elements with eight nodes were employed in this study to obtain appropriate results regarding the deformation behavior of the workpiece during wire flat rolling.

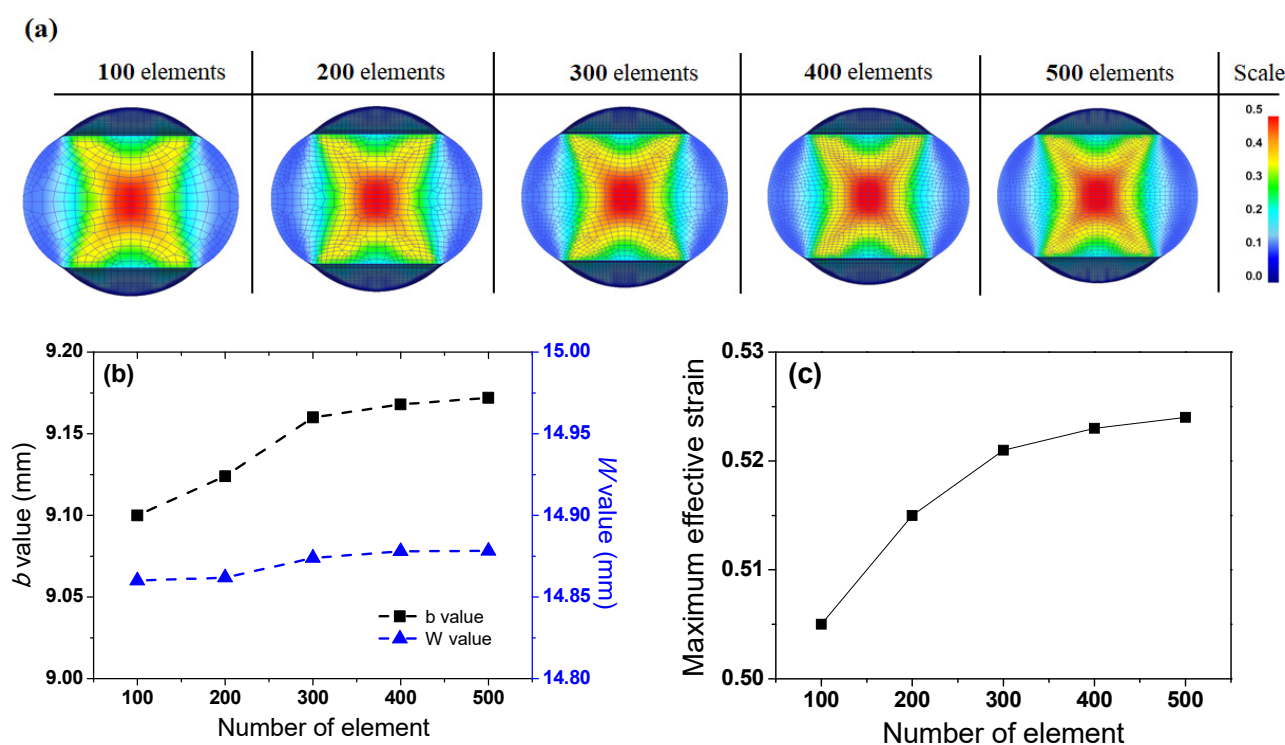


Figure 3. Comparison of (a) effective strain contours, (b) W and b , and (c) ϵ_{max} of the wire with the number of elements at a roll diameter of 400 mm.

2.5. Model Validation

During the general forming process, the FE model is typically validated by comparing the external imposed force for the deformation. In this study, since shape control is a large issue in the wire flat rolling industry, the shape changes between the experimental and simulated results were compared to validate the results of the FE analysis. Figure 4a presents the b and W of the simulated results with R_h , that is, 10%, 20%, 30%, and 40%, at a roll diameter of 400 mm. Both b and W increased with R_h . Figure 4b compares W and b from the FE analysis with the experimental results. The values from the FE analysis were slightly lower than those of the experiment. The authors believe that the deviation in the numerical and experimental values was primarily associated with the friction coefficient or model selected for the FE analysis in this study. For example, Jiang et al. [24] revealed that the friction conditions along both the rolling and width directions of a workpiece significantly affected the strip shape and profile during the strip flat rolling process. In this study, a constant friction coefficient of 0.15 was used from the previous study [22] and the experiences of the authors. Based on the comparison of the shape change of the flattened

wire with R_h , a higher friction coefficient was necessary to more accurately predict the shape change of the flat-rolled wire because it is known that the lateral spreading of the flat-rolled wire increases with the friction coefficient [25]. In addition, roll flattening also affected the wire shape because the elastic deformation of rolls becomes larger and more important as the strength of the workpiece increases [26]. That is, the effective roll diameter increases during the cold rolling process owing to the roll flattening. In this FE analysis, the roll was considered to be a rigid body, which can lead to a decrease in the b and W values of the flat-rolled wire during FE analysis.

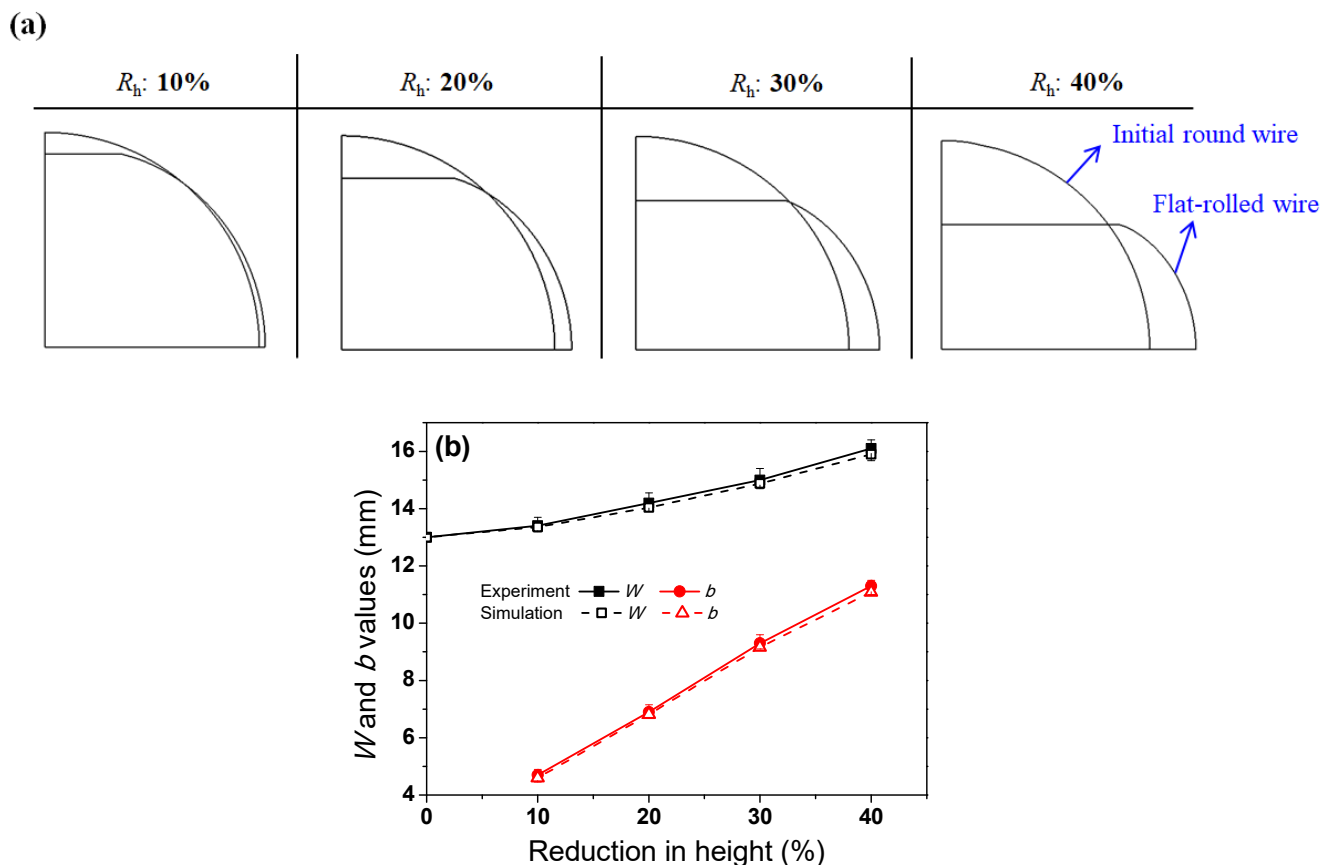


Figure 4. (a) Comparison of shape variation in flat-rolled wire with R_h based on FE analysis and (b) comparison of W and b values obtained from experiment and FE analysis with R_h at a roll diameter of 400 mm.

Overall, although minor errors existed between the results of the experiment and the FE analysis, it can be concluded that the FE model used in this study was adequate for analyzing the flat-rolled wire during the process because the errors of the W and b values between the experiments and simulations were relatively small, namely, within 5%.

3. Results

3.1. Strain Distribution with Roll Diameter

Figure 5a shows a comparison of the effective strains of the wire against the roll diameter. The trends in the strain distribution were similar regardless of the roll diameter. The center region had the maximum effective strain, and the free surface region exhibited the minimum strain. Additionally, the contact surface region exhibited a higher effective strain than the free surface region. MSBs were also observed in all the wires [10]. However, the density of strain distribution was different with the roll diameter. The strain distribution of the flattened wire was more inhomogeneous with the roll diameter, thus the shape of the MSBs was strengthened with the roll diameter.

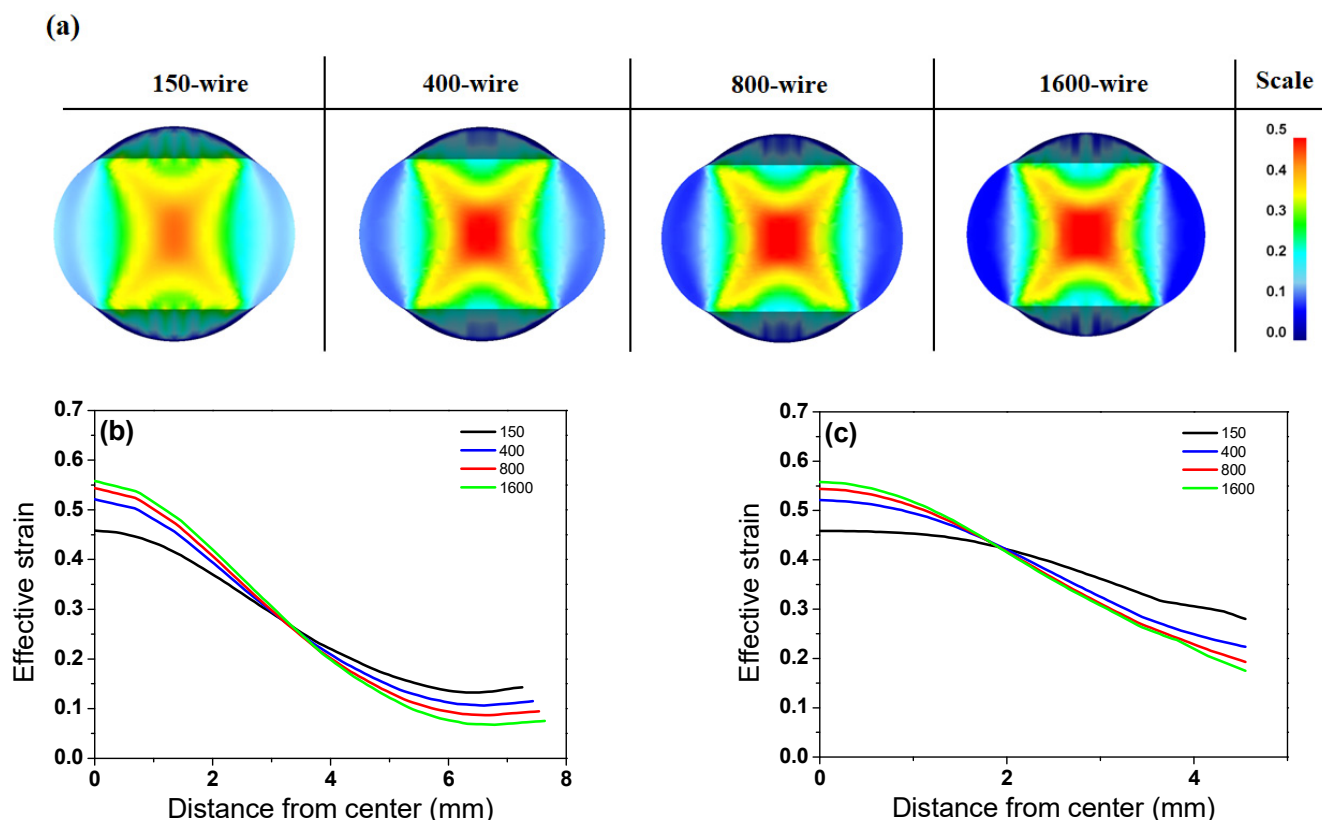


Figure 5. Comparison of effective strain (a) contours and profiles along the (b) horizontal and (c) vertical directions with the roll diameter.

To compare the strain distributions of the flattened wire with the roll diameter comprehensively, the effective strains were extracted based on the strain contour maps. Figure 5a,b compare the extracted effective strain along the horizontal and vertical directions of the wire against the roll diameter. The effective strains at the center region increased with the roll diameter, and those of the free and contact surface regions decreased with the roll diameter, resulting in a larger strain inhomogeneity of the wire with increasing roll diameter. For a better comparison of the inhomogeneity level, the strain inhomogeneity factor (*SIF*), defined as follows, was introduced:

$$SIF = \frac{\varepsilon_{max} - \varepsilon_{min}}{\varepsilon_{ave}} \quad (7)$$

where ε_{ave} and ε_{min} indicate the average and minimum effective strains, respectively. Figure 6a shows the ε_{max} , ε_{min} , and ε_{ave} of the wire against the roll diameter. Regardless of the roll diameter, all the wires had a similar ε_{ave} in both directions. The ε_{max} of the wires increased with the roll diameter, whereas the ε_{min} decreased along both the horizontal and vertical directions of the wire with the roll diameter. Figure 6b compares the strain inhomogeneity factor along both the horizontal direction (SIF_h) and vertical direction (SIF_v) against the roll diameter. Regardless of the roll diameter, SIF_h was higher than SIF_v , which is consistent with previous results [1,4]. It is evident that the *SIF* increased with the roll diameter.

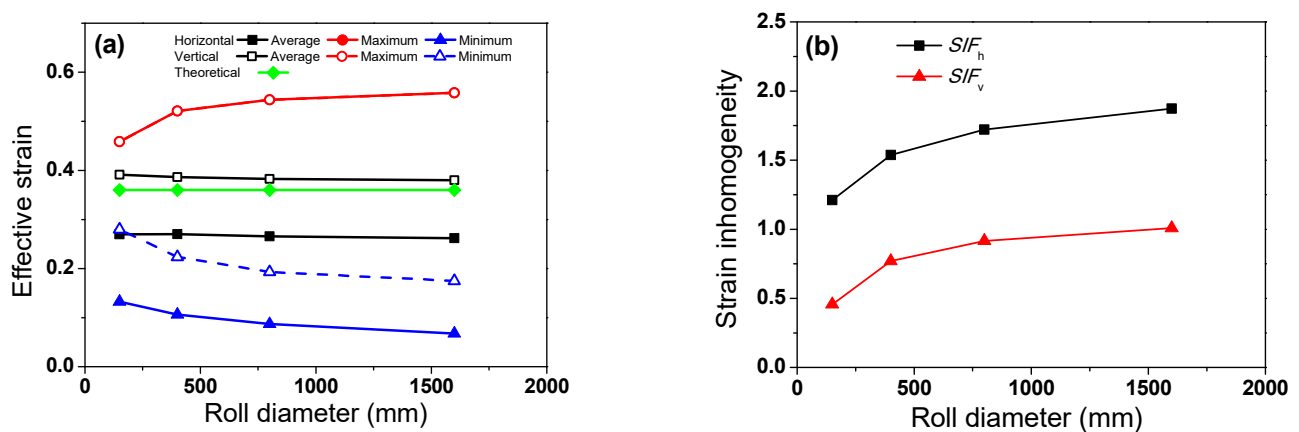


Figure 6. Comparison of the (a) ϵ_{max} , ϵ_{min} , and ϵ_{ave} along the horizontal and vertical directions of the flattened wire and (b) SIF_h and SIF_v of the wire against roll diameter. Theoretical strain was obtained using Equation (3).

3.2. Deformation Shape with Roll Diameter

Figure 7a shows a comparison of the wire shape during wire flat rolling, and Figure 7b shows the variations in b and W with respect to the roll diameter. The b and W of the flattened wires increased as the roll diameter increased. Lambiase and Ilio [27] reported that W increases with the roll diameter during wire drawing with a flat roll, which is consistent with the present result. As the spreading of the wire increased with the roll diameter, R_A decreased with the roll diameter, as shown in Figure 7c. Meanwhile, it is noteworthy that R_A was approximately half the value of R_{it} owing to the significant spreading effect of the workpiece during wire flat rolling.

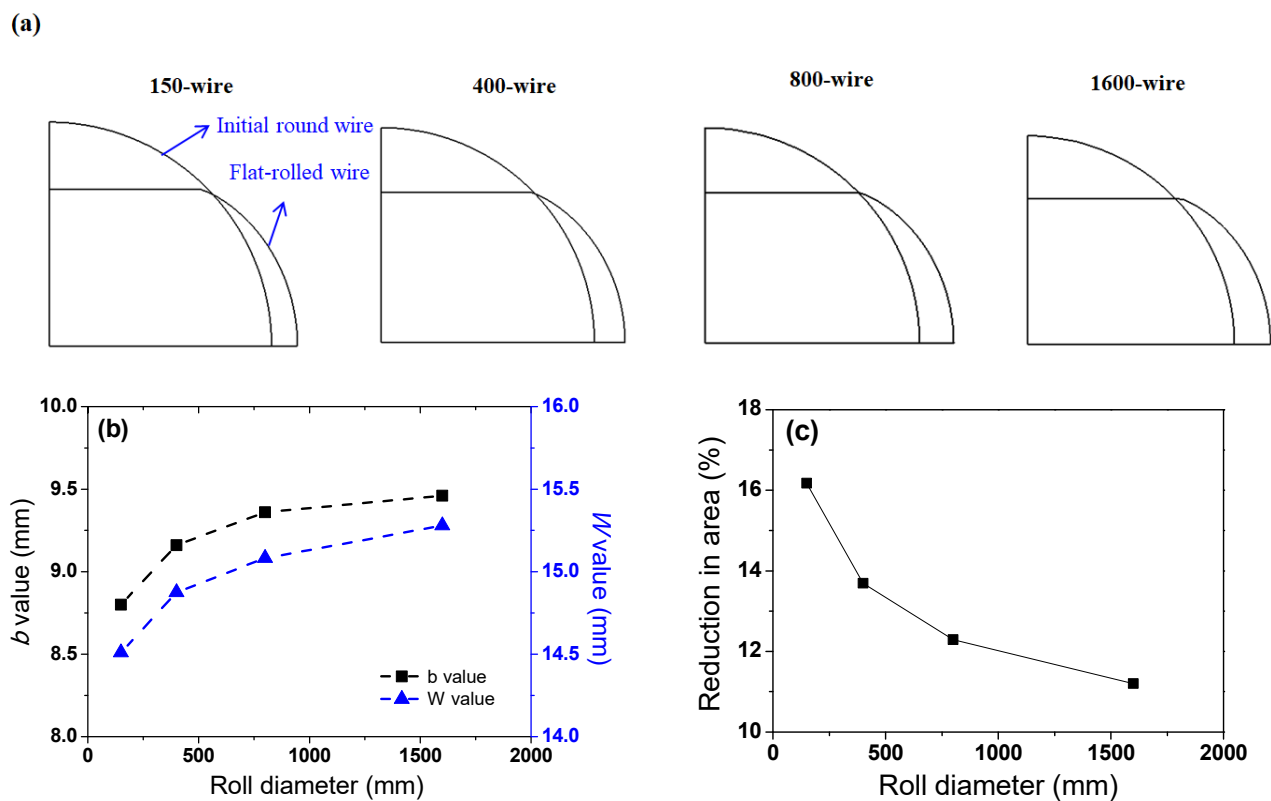


Figure 7. Comparison of (a) shape change, (b) b and W , and (c) R_A against roll diameter.

3.3. Contact Area and Pressure Distribution with Roll Diameter

The contact area and its pressure distribution in the workpiece and roll interface have a great effect on the product shape, roll force, temperature drop, surface properties, production costs, and roll wear during the rolling process. Therefore, the evaluation of the contact pressure in the roll bite is essential to gain a better understanding of the wire flat rolling process. It is known that the distribution of the contact pressure during the rolling process depends on R_h , friction at the workpiece and roll interface, and material properties [5,27–31]. Figure 8 shows the distribution of the normal contact pressure on the wire surface with the roll diameter. The contour of the normal contact pressure on the wire exhibited similar patterns regardless of the roll diameter. The contact pressure showed higher values at the entry, edge, and exit zones of the contact area. This shape of the contact pressure distribution was reported in earlier studies [32,33]. Summarizing the literature above, the higher contact pressures in the entry and edge zones of the contact area are explained by the restrictions caused by the more rigid surrounding material that deforms elastically. In addition, the higher contact pressure on the exit zone of the contact area is attributable to the strain hardening effect of the metal during the process. Figure 9 shows a comparison of the effective stress distribution of the wire along the rolling direction. The similar effective stress distributions of the wire, regardless of the roll diameter, partially supported the present similar contact pressure distributions.

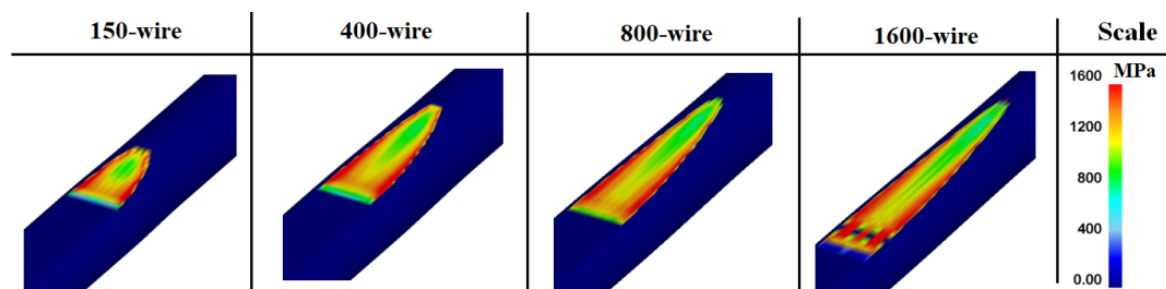


Figure 8. Comparison of the normal contact pressure on the wire surface with the roll diameter during wire flat rolling.

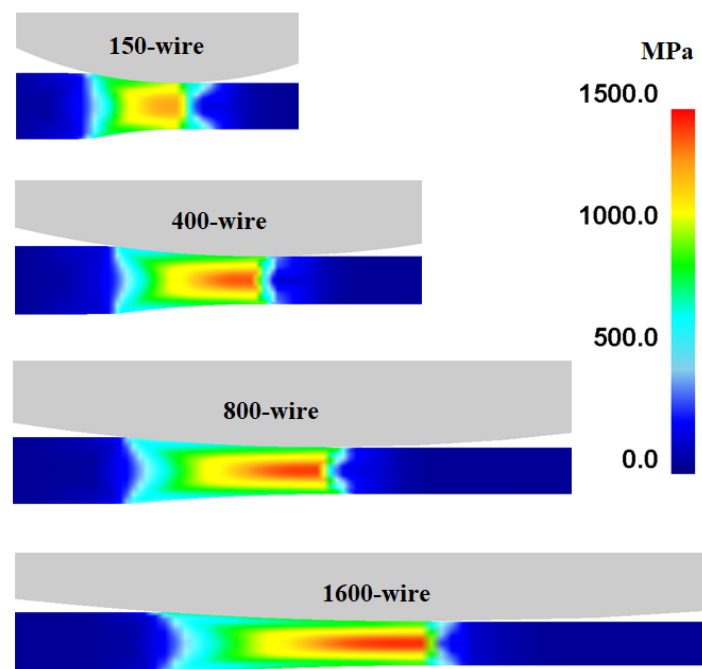


Figure 9. Comparison of the effective stress along the rolling direction of the wire with the roll diameter during wire flat rolling.

Meanwhile, the contact area increased with the roll diameter owing to the increased contact length (L) of the workpiece and roll. Figure 10a shows the contact angle (α) with the roll diameter. The value of α was derived based on the geometrical condition of the wire flat rolling process (Figure 1) as follows:

$$\alpha = \cos^{-1} \left(\frac{D - \Delta h}{D} \right) \quad (8)$$

where Δh indicates the height reduction, i.e., $h_0 - h_1$. Figure 10b compares L with the roll diameter. Although α decreased with the roll diameter, L increased gradually with the roll diameter owing to the increased roll size. During the plate or strip flat rolling process, it was reported that L increases with the roll diameter and R_h as follows [18]:

$$L = \sqrt{\frac{1}{2} D \cdot R_h} \quad (9)$$

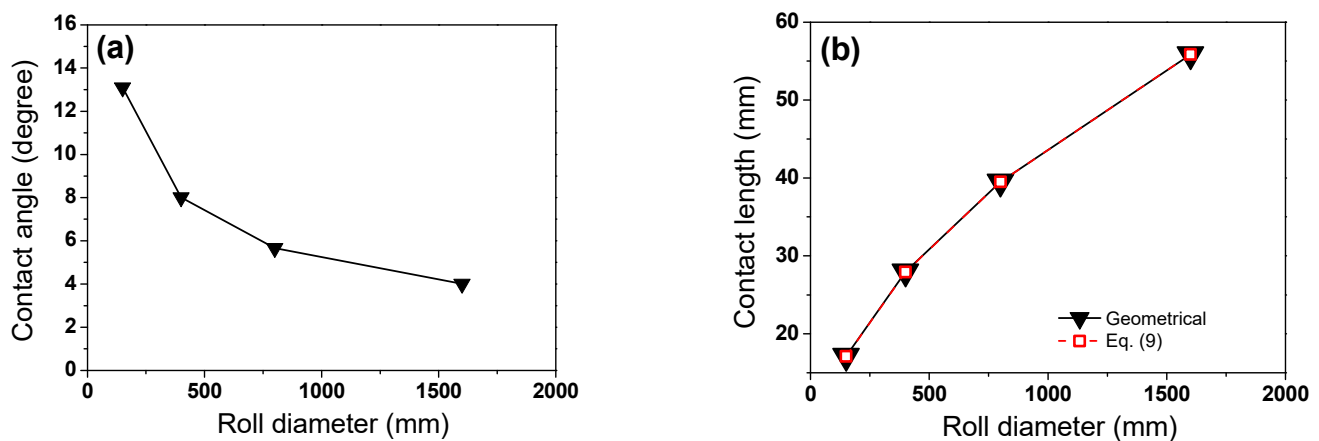


Figure 10. Variations in (a) α and (b) L with the roll diameter during wire flat rolling.

Figure 10b also shows a comparison between the geometrically derived L and the L value obtained using Equation (9). The equation above predicted the L of the wire well during wire flat rolling. Obviously, L increased with increasing roll diameter during wire flat rolling.

3.4. Damage Value with Roll Diameter

The damage value of the wire was analyzed during the process to evaluate the formability with the roll diameter. In this study, the normalized Cockcroft and Latham fracture criterion [34,35] was applied as follows:

$$D = \int_0^{\epsilon_f} \frac{\sigma^*}{\bar{\sigma}} d\bar{\epsilon} \quad (10)$$

where σ^* is the maximum principal tensile stress and $\bar{\sigma}$ is the von Mises equivalent stress. Figure 11a compares the contour of the damage value in the wire with the roll diameter. The distribution of the damage value varied with the roll diameter. The free surface region tended to have the peak damage value during wire flat rolling, which is consistent with previous results using hardening material by Cao et al. [36] and Masse et al. [12]. However, the center region exhibited the maximum damage value as the roll diameter increased, as shown in Figure 11b,c.

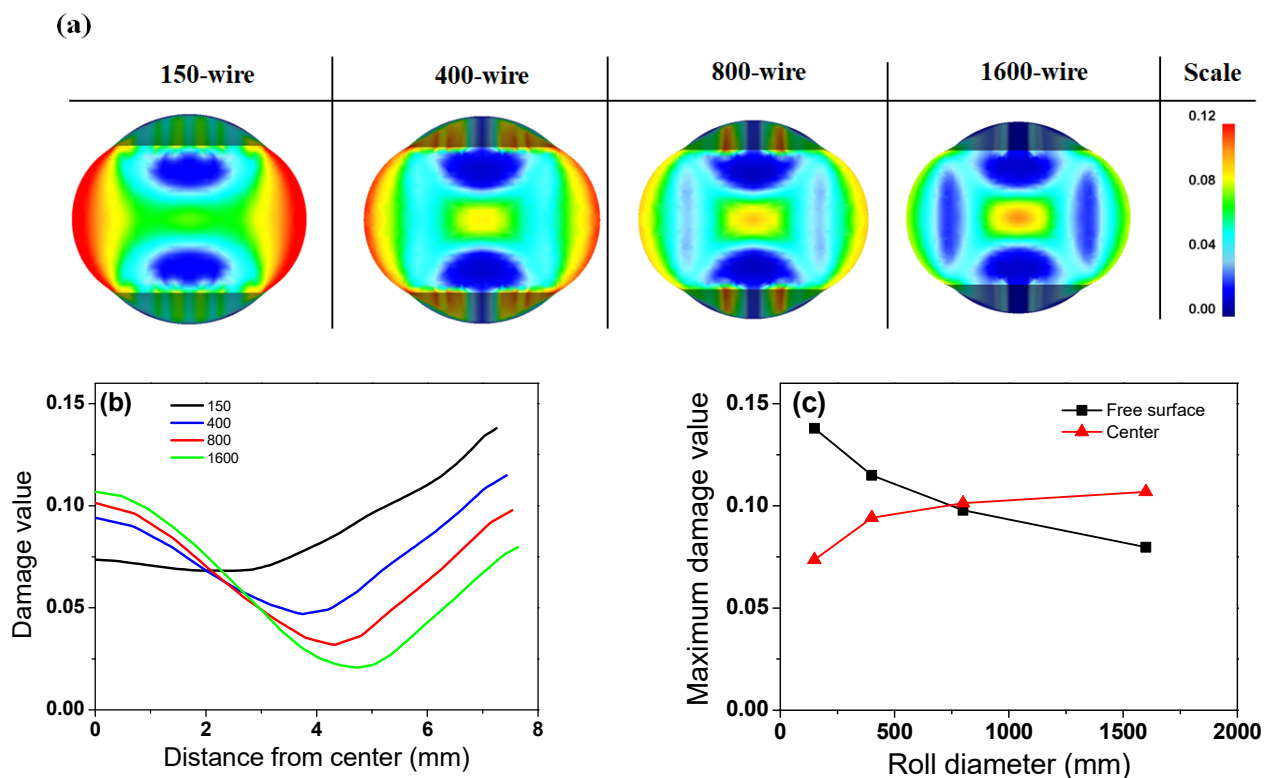


Figure 11. Comparison of the (a) contour of the damage value in the wire, (b) profile of the damage value along the horizontal direction, and (c) the maximum damage value at free surface and center regions with the roll diameter.

4. Discussion

The different behaviors of shape change, strain distribution, and damage value of the wire with the roll diameter during wire flat rolling must be evaluated. First, each strain imposed on the flat-rolled wire was compared with the direction. During the rolling process, the compressive stress imposed on the workpiece by the roll mainly deformed the workpiece in three directions (Figure 1), that is, the height, longitudinal, and transverse directions of the workpiece, which are typically known as reduction, elongation, and spreading, respectively. Figure 12 compares the strain contours in the three directions of the wire with the roll diameter. The reduction exhibited similar contours regardless of the roll diameter, and the spreading tended to concentrate on the center region with increasing roll diameter. Interestingly, the elongation decreased with increasing roll diameter. Figure 13 shows a comparison of the average elongation with the roll diameter. The decreased elongation with the roll diameter increased b and W , resulting in a decrease in R_A with the roll diameter (Figure 7). The decreased elongation with the roll diameter also decreased the ε_{min} of the wire at the free and contact surface regions, leading to an increase in SIF_h and SIF_v with the roll diameter (Figure 6). Accordingly, both the shape change and strain distribution of the specimen during wire flat rolling were associated significantly with the elongation of the wire during the process.

The decreased elongation of the wire with the roll diameter was highly dependent on L . The increased L with the roll diameter (Figure 10) rendered the frictional effect more prominent owing to the higher contact surface. That is, the increased contact area between the wire and roll resulting from the increased L increased the frictional effect along the longitudinal direction of the wire ($F_{\mu length}$) compared with the transverse direction of the wire ($F_{\mu width}$), as shown in Figure 14. The increased $F_{\mu length}$ decreased the elongation, leading to an increase in the spreading, including b and W owing to the conservation of volume during the plastic deformation. Esteban et al. [37] reported that lateral spreading increases as the friction coefficient increases during the plate flat rolling process.

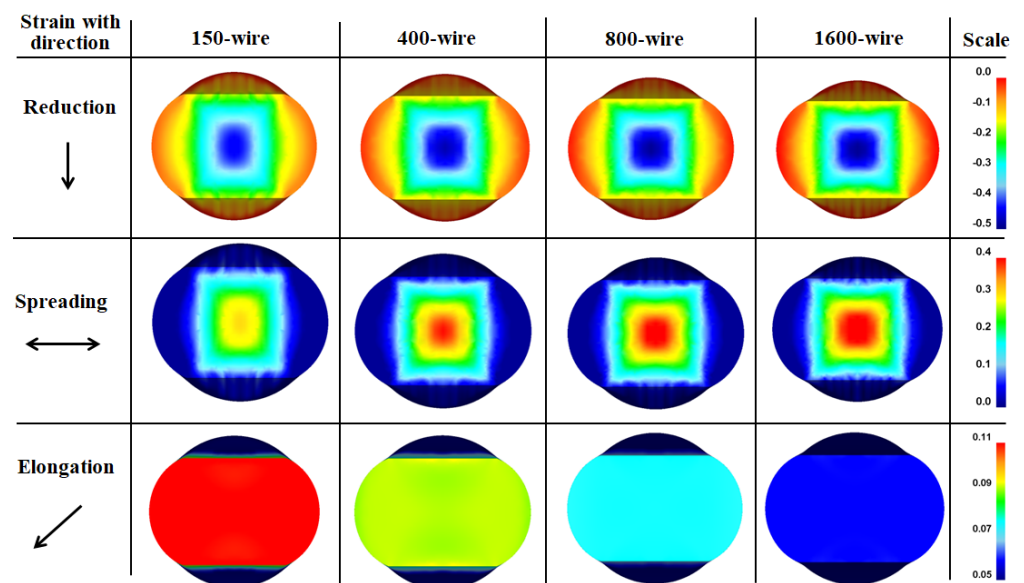


Figure 12. Comparison of the strain contours at three directions of the wire with the roll diameter.

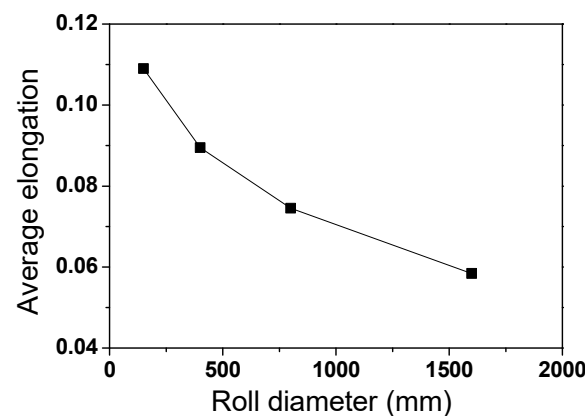


Figure 13. Comparison of the average elongation of the wire against roll diameter.

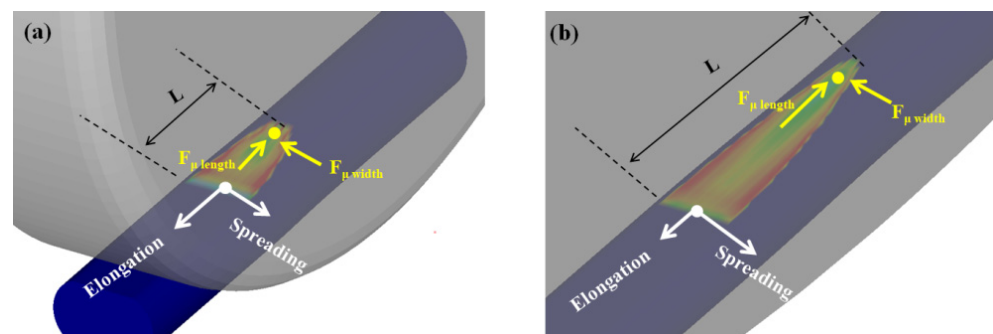


Figure 14. Schematic illustration of the frictional effect at the wire and roll interface with (a) small roll and (b) large roll during wire flat rolling.

Meanwhile, it is known that a higher frictional effect concentrates the stress in the center region during the compression-type forming process. The rolling process mainly deformed the material under the compression stress state; therefore, the higher frictional effect with increasing roll diameter due to the higher L led to an increase in the ε_{max} at the center region of the wire. In other words, the strain concentration in the center region was stronger as the roll diameter increased, this is attributable to the high L during wire flat

rolling. Kazeminezhad and Taheri [1] revealed that the strain inhomogeneity of a flat-rolled wire increases as the friction coefficient at the interface between the wire and roll increases. As a result, the underlying cause of the strain distribution and shape change of the flattened wire was highly related to L during deformation.

The damage value analysis showed that the wire fabricated using the small roll was easy to fracture in the free surface region; whereas, the wire manufactured by the large roll tended to be fractured in the center region (Figure 11). For the wires with a small roll, the high elongation (σ^*) and small $\bar{\sigma}$ in the free surface region were related to the fracture in this region. By contrast, the high spreading (σ^*) in the center region of the wire fabricated using large roll (Figure 12) yielded a high damage value in this region. Accordingly, the wire can be fractured with the different manner depending on the roll diameter during wire flat rolling. For instance, cracks occurred in the free surface region along the rolling direction in the 150-wire; whereas, cracks were generated in the center region along the spreading direction in the 1600-wire. It is noteworthy that the optimum roll diameter was in existence during wire flat rolling from the perspective of the damage value. In this study, the 800-wire exhibited the minimum damage value, as shown in Figure 11c. In addition, the damage value can vary with materials because σ^* and $\bar{\sigma}$ in Equation (10) varied with n value of the material. In other words, the optimum roll size was different with materials during wire flat rolling.

5. Conclusions

The influence of the roll diameter on the strain distribution, shape change, contact pressure, and damage value of the workpiece was comprehensively investigated during wire flat rolling. The conclusions obtained are as follows:

1. The strain inhomogeneity of the flat-rolled wire increased with the roll diameter; therefore, the MSBs were strengthened with the roll diameter during wire flat rolling.
2. The b and W of the wire increased as the roll diameter increased, leading to a decrease in R_A with the roll diameter.
3. The contour of the normal contact pressure on the wire surface exhibited similar patterns regardless of the roll diameter. The contact pressure of the wire was higher at the entry, edge, and exit zones in the contact area.
4. The distribution of the damage value varied with the roll diameter. The free surface region tended to have the peak damage value during wire flat rolling; however, the center region exhibited the maximum damage value as the roll diameter increased. The optimum roll diameter was in existence during wire flat rolling from the perspective of the damage value.
5. The underlying cause of the different strain inhomogeneities, shape changes, and damage values of the flattened wire was the different contact lengths originating from the different roll diameters during wire flat rolling.

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