Enhanced Homogeneity of a Flat-rolled Wire in Twinning-induced Plasticity Steel Using the Pass Schedule Design

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The effects of reduction in height per pass, roll diameter, and friction coefficient on the homogeneity of mechanical properties and shape change in flat-rolled twinning-induced plasticity steel wire were investigated. The goal was to improve the homogeneity of mechanical properties of a wire with area during flat rolling process using a numerical simulation, a hardness test, and electron backscatter diffraction techniques. Reduction in height per pass and roll diameter had large influences on both strain inhomogeneity and lateral spread of flat-rolled wire. Strain inhomogeneity and lateral spread increased with increasing the reduction in height per pass and roll diameter due to the higher length of the contact area. The underlying mechanism for the strain inhomogeneity and lateral spread of flat-rolled wire was highly related to the length of contact area. Hence, the length of the contact area needed reduction through controlling process conditions to improve the strain homogeneity of the flat-rolled wire. The effect of friction coefficient on lateral spread was negligible, whereas strain inhomogeneity slightly increased with friction coefficient. The combination of high and low reduction in height per pass with a smaller roll diameter improved the homogeneity of mechanical properties and microstructure over the area of the flat-rolled wire. Based on the results of numerical simulation and experimental test, a new practical strategy is proposed to achieve greater homogeneity of mechanical properties over the area of flat-rolled wire, which could be of great applicability in industrial fields.

KEY WORDS: twinning-induced plasticity steel; flat rolled wire; strain inhomogeneity; pass schedule.

1. Introduction

Flat-rolled wires are used in many applications, such as springs, guide rails, windshield wipers, and saw blades.¹⁾ During the flat wire rolling process, the initial round-shaped wire is deformed into a flat wire by two flat rolls at room temperature.²⁾ Typically, there are two significant issues in the flat wire rolling industry. The first is shape control of the flat-rolled wire since direct shape control of wire is impossible during the flat wire rolling process. In other words, a lateral spread always occurs in free surface of wire,³⁾ and undesirable shapes and sizes of wire lead to unsatisfactory products. Consequently, several studies have been conducted about the influence of process conditions such as height reduction, friction, wire size, and rolling velocity on the lateral spread of wire using empirical and/or numerical methods.^{1,4–8)} The studies reported that the lateral spread of wire increased with height reduction and was not dependent on rolling velocity. The second issue is the inhomogeneity of mechanical properties of flat-rolled wire

with area due to the applied stress states and initial shape of the wire during the flat wire rolling process. Therefore, strain distribution of flat-rolled wire has been investigated using finite element (FE) analysis and hardness test.^{9–12)} It was found that the inhomogeneity of mechanical properties increased with increasing friction coefficient and decreasing reduction in height. Of the above two issues, the inhomogeneity of mechanical properties of flat-rolled wire is more critical in industry since it is highly related to the product life or failure. Besides, as the strength of flat-rolled wire applications gradually increases, flat-rolled wire products are increasingly required to have homogeneous mechanical properties with area.

Recently, Hwang *et al.* suggested that twinning-induced plasticity (TWIP) steel is a promising material for high strength wire rod products^{13,14)} including flat-rolled wire applications¹⁵⁾ because TWIP steels meet the strict property requirements for wire rod products originating from their outstanding combination of strength and ductility.^{16–24)} Moreover, TWIP steels have a higher resistance to hydrogen-delayed fracture in comparison with conventional plain carbon steels that are typically used for wire rod applica-

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tions. This is mainly due to the face-centered cubic (FCC) structure of TWIP steel.^{25,26)}

Over the past three decades, although several works have reported on the effect of process conditions on the inhomogeneity of mechanical properties of flat-rolled wire with area,^{9–12)} most of the works have been conducted qualitatively. Furthermore, no articles have been published on the direct relationship between process conditions and the homogeneity of mechanical properties of flat-rolled wire. This has made it difficult to directly apply the reported results to industry. Consequently, the influence of process parameters on the areal homogeneity of mechanical properties of flat-rolled wire is ambiguous. The literature review and the author's experiences have stimulated an additional investigation into the relationship between process conditions and the inhomogeneity of mechanical properties in flat-rolled wire, especially for high strength TWIP steels.

Thus, the present study focuses on the influence of process conditions on the inhomogeneity of mechanical properties in flat-rolled TWIP steel wire with the goal of improving the homogeneity of mechanical properties in the wire. Due to the limited research resource, a parametric study was conducted using numerical simulation to analyze the effect of each process condition on the inhomogeneity of mechanical properties of wire and to discover optimum process conditions. Subsequently, flat wire rolling tests were conducted for two cases: the standard and the derived new process conditions. The results were compared using a hardness test and electron backscatter diffraction (EBSD) techniques to validate the process conditions suggested by numerical simulation.

2. Numerical and Experimental Procedures

2.1. Numerical Procedure

Flat-rolled wire experiences three-dimensional (3D) inhomogeneous deformation¹⁵⁾ due to the initial round shape of the wire, indicating that 3D numerical analysis is strongly necessary in understanding the stress and strain distribution of flat-rolled wire. Thus, DEFORM FE commercial software version 11.0 with a 3D module was used to analyze the flat rolling process.

In order to run the numerical simulation, the stress-strain curves are necessary for input data and are generally acquired based on the uniaxial tensile or compressive curve. Typically, the effect of strain rate is not considered during the cold forming process. However, it is well known that TWIP steel is a strain rate sensitive material.^{27–31)} C-bearing TWIP steels exhibit both negative strain rate sensitivity (NSRS) and positive strain rate sensitivity (PSRS) with strain rate. Accordingly, in obtaining more accurate numerical results, the effect of strain rate needed consideration in the input stress-strain curve, which is modeled as follows for the current TWIP steel:¹⁵⁾

$$\sigma = 1884\varepsilon^{0.43} \left(\frac{\dot{\varepsilon}}{10^{-3}} \right)^{-0.014} \dots\dots\dots (1)$$

Since hot-rolled steel was used as an initial wire, the wire

was assumed to be isotropic and rigid plastic material in this study. And, the kinematic hardening effect of TWIP steel³²⁾ was ignored in the current numerical simulation because the strain path change was small during the flat wire rolling process.

All the flat rolls were assumed to be rigid, and the roll diameter was changed from 200 to 1 000 mm to understand the influence of roll diameter on the homogeneity of mechanical properties of the wire as listed in **Table 1**. To evaluate the effect of height reduction per pass, the wire was rolled with average reductions in height per pass of 5, 10, and 35% (**Tables 1 and 2**). Reduction in height (R_h) in percent is calculated using the following simple equation:

$$R_h = \frac{h_0 - h_1}{h_0} \times 100(\%) \dots\dots\dots (2)$$

where h_0 and h_1 refer to the initial and final heights of the wire, respectively. The shear friction coefficient between wire and rolls was also varied from 0.2 to 0.8 in order to understand the frictional effect on the strain homogeneity and wire shape. Due to the slow rolling speed of 5 RPM, the effect of temperature rise was not considered during process, *i.e.*, isothermal condition. The average strain rate was evaluated using Eq. (3), which is typically used for calculating the average strain rate of flat-rolled plate or sheet:

$$\dot{\varepsilon}_{ave} = \frac{v}{\sqrt{R_d(h_0 - h_1)}} \ln \frac{h_0}{h_1} \dots\dots\dots (3)$$

where v means the circumferential speed of roll. Although R_d means the deformed roll radius, it was taken to be the roll radius (R) in the current work. The other process parameters and pass schedules are summarized in Tables 1 and 2.

To reduce the computational time and cost, only the

Table 1. Process parameters during flat wire rolling process in this simulation.

Process parameters	Values		
	Lower limit	Standard value	Upper limit
Average reduction in height per pass (%)	5 (B)	10 (A)	35 (C)
Roll diameter (mm)	200	400	1 000
Friction coefficient (μ)	0.2	0.3	0.8

Table 2. Pass schedules of flat wire rolling process for this study.

No. of pass	Roll gap (mm)				Reduction in height per pass (%)			
	A	B	C	D	A	B	C	D
1	11.63	12.3	8.45	10.70	10.5	5.4	35	17.7
2	10.50	11.63	–	9.45	9.7	5.4	–	11.7
3	9.40	11.05	–	8.90	10.5	5.0	–	5.8
4	8.45	10.50	–	8.45	10.1	5.0	–	5.1
5	–	9.94	–	–	–	5.3	–	–
6	–	9.40	–	–	–	5.4	–	–
7	–	8.92	–	–	–	5.1	–	–
8	–	8.45	–	–	–	5.3	–	–

quarter section of full geometry was calculated as the geometric condition of the flat wire rolling process is highly symmetric. The total number of mesh was approximately 15 000, and 300 brick-type mesh was used in the cross-section of wire.

2.2. Experimental Procedure

A steel ingot with an analyzed chemical composition of Fe-17.1Mn-0.66C-1.75Al in weight percent was fabricated by vacuum induction method. According to the thermodynamics approach of Saeed-Akbari *et al.*,³³⁾ the calculated stacking fault energy (SFE) of this steel was 27.2 mJ/m² at room temperature, indicating that the dominant plastic deformation mechanism is twinning and dislocation slip, while ε -martensite transformation should be suppressed during deformation.^{34,35)} The cast ingot, 125 mm in thickness and 50 kg in weight, was homogenized at 1 200°C for 3 h. It was then hot-rolled to a plate of 20 mm in thickness at temperatures ranging from 950 to 1 150°C, followed by air cooling at room temperature in order to simulate hot rod rolling process.

For the flat wire rolling tests, the hot-rolled plate was machined into several round bars with diameters of 13 mm. Flat wire rolling tests were performed with two pass schedules. The wires were rolled up to four pass by two rolls with a diameter of 400 mm in the A pass schedule and a diameter of 300 mm in the D pass schedule without lubricant, as shown in Table 2. Rolling speed was set as 5 RPM to ignore the temperature rise effect in both pass schedules. Their deformation behaviors were carefully analyzed and compared.

Mechanical properties were measured by tensile test and the Vickers microhardness test. Tensile specimens with gauge diameters of 5 mm and lengths of 25 mm were prepared along the rolling direction. They were elongated at an initial strain rate of 10^{-3} s^{-1} using an Instron machine at room temperature. The Vickers microhardness test was employed using an applied load of 9.8 N on the cross-sectional plane perpendicular to the rolling direction.

The microstructure of the flat-rolled wire was characterized by EBSD on the cross-sectional area of samples perpendicular to the rolling direction. Specimens were carefully prepared by mechanical polishing using diamond pastes and

colloidal silica slurry. A field emission scanning electron microscope (SEM) equipped with a TSL EBSD system was used at an acceleration voltage of 20 kV and a specimen tilting angle of 70°. EBSD data were acquired using the step size of 0.1 μm , and were analyzed using the commercial software, the orientation imaging microscopy (OIM).

3. Results and Discussion

3.1. Analysis of Numerical Simulation

3.1.1. Validation of Numerical Model

Before presenting the results of numerical simulation, the accuracy of the numerical model was validated by comparing the measured and numerically simulated geometry of the flat-rolled TWIP steel wire. **Figure 1(a)** shows a schematic of the cross-sectional shape of flat-rolled wire and terminologies used in this study, and Fig. 1(b) shows the comparison of measured and numerically-simulated widths of contact area (b) and lateral spread (W) values in the standard A pass schedule as shown in Table 2 as a function of total reduction in height. Obviously, the W and b values increased with total reduction in height, and these values obtained by FE analysis were in good agreement with the measured ones. However, a close inspection showed that the deviation in W values between the two results increased slightly with increasing total reduction in height. To the best of the author's knowledge, this discrepancy was related to the applied hardening model in this simulation; therefore, a well-designed kinematic hardening model was required to increase the accuracy of results in the deformed wire.³⁶⁾ Overall, it could be concluded that the proposed FE analysis for the flat wire rolling process was sufficient to evaluate the characteristics of shape change and strain distribution with process conditions.

Meanwhile, Kazeminezhad and Karimi Taheri^{1,4)} predicted the b and W values as a function of total reduction in height (Δh) and initial height of wire (h_0) based on plain carbon steels as follows:

$$\frac{W_1}{W_0} = 1.02 \left(\frac{h_0}{h_1} \right)^{0.45} \quad \text{..... (4)}$$

$$b = \sqrt{2\Delta h h_0} \quad \text{..... (5)}$$

Fig. 1. (a) Schematic of cross-sectional shape of flat-rolled wire and terminologies used in this study, and (b) comparison of measured, numerically simulated, and theoretically derived W and b values as a function of total reduction in height. (Online version in color.)

where the subscripts 0 and 1 mean before and after values during flat rolling process, respectively. As shown in Fig. 1(b), the W and b values of TWIP steel were lower than those of plain carbon steel based on the theoretically suggested relationships by Kazeminezhad and Karimi Taheri. Hwang¹⁵⁾ suggested that this is due to the different strain hardening behaviors between plain carbon steels and TWIP steel. That is, the strain hardening exponents of TWIP steel are much higher than those of plain carbon steels.

3.1.2. Effect of Reduction in Height Per Pass

Figures 2(a)–2(c) compares the contours of effective strain of flat-rolled wire at the final pass with changing the reduction in height per pass. It was clearly observed that the strain distribution in flat-rolled wire was complex, and its strain distribution was similar to that of the compression test.³⁷⁾ In other words, the flat-rolled wire had two macroscopic shear bands with high effective strain. This kind of macroscopic shear band has been well reported in several compression-type plastic forming processes, such as side pressing process, wire drawing process with idle flat rolls, caliber rolling process, and flat wire rolling process.^{9,38–40)} This undesirable strain distribution under the compressive stress is attributed to the strongly restricted plastic flow in the region near the specimen and die interface owing to the friction effect. The effective strain around the macroscopic shear bands was much higher than that of the other regions, which meant that macroscopic shear bands led to the inhomogeneity of mechanical properties of the flat-rolled wire. In other words, we could improve the homogeneity of mechanical properties of flat-rolled wire by suppressing the macroscopic shear bands.

Generally, the center area tends to have the maximum effective strain, while the free surface area tends to have the minimum effective strain. However, the distribution of effective strain of wire with area was significantly different

with reduction in height per pass. The smaller height reduction per pass increased the strain homogeneity during the flat wire rolling process, *i.e.*, the strain tended to localize around the wire and roll contact area at small reductions in height per pass because the external rolling force from the roll contact area did not penetrate the core area. This led to a prevention of strain concentration on the center area, finally increasing the strain homogeneity of the flat-rolled wire. As an example of this phenomenon, the wire processed by the B pass schedule had a relatively higher effective strain near the roll contact area, which is beneficial for practical use in flat-rolled wire products. However, it should be noted that the B pass schedule is impractical to apply in a real plant due to the lower operating efficiency. The effective strains extracted from the contour maps along the horizontal and vertical directions (Fig. 1(a)) are compared in Fig. 2(d) with the reduction in height per pass. The position of the maximum effective strain was changed with the reduction in height per pass, whereas the free surface area always had the minimum value of effective strain. The deviation of effective strain along the horizontal direction was higher than that of the vertical direction, which was in good agreement with the result of the flat-rolled Cu wire.¹⁰⁾ Clearly, a smaller height reduction per pass increased the homogeneity of flat-rolled wire.

Figure 2(e) shows the variation in b and W values with the reduction in height per pass. The b and W values increased with increasing the height reduction per pass since the length of the contact area increased with increasing the reduction in height per pass, which will be explained in the next section in more detail.

3.1.3. Effect of Roll Diameter

To understand the effect of roll diameter on the strain homogeneity and lateral spread of flat-rolled wire, the roll diameter was varied with 200, 400, and 1 000 mm. **Figures**

Fig. 2. Contours of effective strain of flat-rolled wires with different average reduction in height per pass of (a) 5%, (b) 10%, and (c) 35%. Comparison of (d) effective strain along the horizontal and vertical directions, and (e) W and b values with total reduction in height. (Online version in color.)

Fig. 3. Contours of effective strain of flat-rolled wires with roll diameters of (a) 200, (b) 400, and (c) 1 000 mm at the final pass. Comparison of (d) effective strain along the horizontal and vertical directions, and (e) W and b values with roll diameter. (Online version in color.)

Fig. 4. Numerical results of contact length along the rolling direction in wire-roll interface with roll diameters of (a) 200, (b) 400, (c) 1 000 mm, and (d) comparison of contact length with roll diameter at the final pass. (Online version in color.)

3(a)–3(c) shows the distribution of effective strain of rolled wire at the final pass with roll diameter. Interestingly, the distribution of effective strain with area was quite different with roll diameter. Both inhomogeneity and lateral spread of wire increased with increasing roll diameter as shown in Figs. 3(d) and 3(e) as the length of contact area (L) increased with increasing roll diameter. It is well known that L increases with increasing roll diameter during the flat rolling process of plate or strip as follows:⁴¹⁾

$$L = \sqrt{R\Delta h} \dots\dots\dots (6)$$

Evidently, L also increased with increasing roll diameter

during the flat wire rolling process as shown in **Fig. 4**, resulting in increasing frictional effect, leading to an increasing W value. It is worth noting that L value during flat rolling process of wire was also in good agreement with Eq. (6) derived from flat rolling process of the plate. In addition, higher frictional stress on the surface area resulting from the higher L value made the plastic flow difficult on the roll contact surface area, resulting in the worse homogeneity of wire with area. Namely, the strain was concentrated in the center area with increasing roll diameter, which was highly related to the higher L value with increasing roll diameter. Meanwhile, the influence of

reduction in height per pass on strain inhomogeneity and lateral spread in the section of 3.1.2 could also be explained by the variation in L value with reduction in height per pass as given in Eq. (6). Therefore, the underlying mechanism for the strain inhomogeneity and lateral spread of the flat-rolled wire was highly related to L value during plastic deformation.

3.1.4. Effect of Friction

Figures 5(a)–5(c) shows the distribution of effective strain in the cross-section of the flat-rolled wire at the final pass with changing friction coefficient. The trend in strain distribution of the flat-rolled wire was similar with the friction coefficient; however, the strain inhomogeneity of the wire with area increased with increasing friction coefficient (Fig. 5(d)) due to the strongly restricted flow near the wire-die interface stemming from the higher frictional effect. Meanwhile, the effect of friction coefficient on geometrical characteristics of the flat-rolled wire was almost negligible as shown in Fig. 5(e).

3.1.5. Improved Process Condition for High Quality Flat-rolled Wire

According to the above numerical results, a smaller reduction in height per pass improved the strain homogeneity of the flat-rolled wire. However, this strategy increased the total number of pass needed to fabricate the desired shape and size of the flat-rolled wire product, which reduced both productivity and efficiency of the plastic forming process. The most effective idea for solving the above problem was to distribute the height reduction per pass at the specific total number of pass. The D pass schedule gradually decreases the height reduction per pass with increasing rolling pass as given in Table 2. *I.e.*, the concept of D pass schedule is to design the height reduction per pass considering both plant productivity and product quality. The final wire shape and size was obtained using the high reduction

in height per pass, and the strain homogeneity of the wire was acquired using the low reduction in height per pass. In the D pass schedule, roll diameter was also reduced from 400 to 300 mm for a better homogeneity of the flat-rolled wire with area from the results in section 3.1.3. Based on the author's experiences, when the ratio of roll diameter to wire diameter was less than approximately 20, the wire was hardly inserted into the roll in the general rolling condition, especially at the first pass; thus, we could not decrease the roll diameter significantly.

Apparently, the weaker shear bands were seen in the flat-rolled wire fabricated by the D pass schedule compared to the wire fabricated by the A pass schedule at the final pass as shown in **Figs. 6(a)** and **6(b)**. The wire subjected to the D pass schedule had higher strain homogeneity with area compared to the wire subjected to the A pass schedule, especially along the vertical direction (Fig. 6(c)). For the flat-rolled wire products, the homogeneity along the vertical direction is more important than that along the horizontal direction. In addition, the author believes that the D pass schedule was a better process condition considering the strain hardening effect of metals as well as shape control at the final pass. Meanwhile, the wire fabricated by the D pass schedule had similar W and b values to that fabricated by the A pass schedule as shown in Fig. 6(d) resulting from the existence of both high and low height reductions per pass in the D pass schedule.

3.2. Analysis of Mechanical Properties and Microstructures

According to the above results of numerical simulation, the wire processed by the D pass schedule exhibited higher product quality. Thus, the D wire was manufactured using the off-line flat rolling simulator and compared with the wire processed by the A pass schedule in order to validate the above numerical results. **Figure 7(a)** displays the initial microstructure of the hot-rolled steel. It consisted primarily

Fig. 5. Contour maps of effective strain of flat-rolled wires with shear friction coefficients of (a) 0.2, (b) 0.3, and (c) 0.8 at the final pass. Comparison of (d) effective strain along the horizontal and vertical directions and (e) W and b values with the friction coefficient. (Online version in color.)

Fig. 6. Contours of effective strain of flat-rolled wire fabricated by (a) standard A pass schedule and (b) improved D pass schedule at the final pass, and comparison of (c) effective strain profiles along the horizontal and vertical directions, and (d) W and b values with pass schedule. (Online version in color.)

Fig. 7. (a) EBSD grain boundary map and (b) engineering tensile stress-strain curve of hot-rolled TWIP steel. Red, black, and blue lines are related to twin boundaries, high angle grain boundaries, and low angle grain boundaries, respectively, *i.e.*, $-\Sigma 3$, $-\theta \geq 15^\circ$, $-15^\circ > \theta \geq 2^\circ$. (Online version in color.)

Fig. 8. Comparison of (a) measured cross-sectional shape and (b) b and W values of flat-rolled wire fabricated by A and D pass schedules at the final pass. (Online version in color.)

of high angle grain boundaries and annealing twin boundaries with an average grain size of 12 μm . The engineering tensile curve of the hot-rolled steel exhibited general charac-

teristics of C-added TWIP steels as shown in Fig. 7(b).^{21,42)} high tensile strength and uniform elongation, small yield strength and post-necking elongation, and strong serrations

in the latter part of curve. As shown in **Fig. 8(a)**, the two flat-rolled wires of different pass schedules were successfully manufactured with no internal nor surface defects. The dimensional accuracy of the two flat-rolled wires is compared in **Fig. 8(b)**: they had an almost similar shape at the final pass, which was in good agreement with the prior result of numerical simulation (**Fig. 6(d)**).

Figure 9(a) compares the measured average hardness of specimens produced by A and D pass schedules with total reduction in height. The average hardness was virtually similar between the two processes; however, a close inspection shows that the D wire had a slightly lower hardness compared to the A wire with increasing rolling passes. Hardness profiles along the horizontal and vertical directions are compared at the final pass as shown in **Fig. 9(b)**. The maximum hardness occurred around the center area, and the free surface area had the minimum value. The inhomogeneity of hardness along the horizontal direction was much higher in comparison with that of the vertical direction, which is also consistent with the results of numerical simulation. The hardness profiles of wire fabricated by the D pass schedule were more homogeneous than those of the A pass schedule, implying that we can produce flat-rolled wires with more homogeneous mechanical properties by controlling the reduction in height per pass and roll diameter during the flat wire rolling process. This result was significantly useful for industrial applications.

To understand the microstructure of flat-rolled wires with the two schedules pass, the final rolled wires were analyzed by EBSD techniques. **Figure 10** compares the inverse pole figure (IPF) maps, image quality (IQ) maps, and Kernel average misorientation (KAM) maps of those flat-rolled wires subjected to the A and D pass schedules at the final pass. Based on the results of numerical simulation and hardness test, four regions were observed at each pass schedule: center, free surface, roll contact surface, and corner as depicted in **Fig. 1(a)**. In the IQ maps, parallel black lines inside austenite grain were $\Sigma 3$ twin boundaries.¹³⁾ The twins were not clearly observed owing to the high deformation of these specimens, but they could provide helpful information about the tendency of deformation twinning. Regardless of pass schedule and area, most of the grains had deformation twin. The twin density at the free surface area was lowest regardless of pass schedule due to the lowest effective strain (**Fig. 6**). For a better comparison of the

deformation behaviors of the flat-rolled wires between A and D pass schedules, KAM value was analyzed and compared with the maximum misorientation angle of 5° at the final pass. It is known that the spatial orientation gradient reflects the amount of deformation or geometrically necessary dislocation (GND) density.⁴³⁾ The difference in KAM values was observed among the four individual sites for both pass schedules. Compared to the D wire, the A wire had a higher KAM value at the center and corner areas due to the strong macroscopic shear bands in the A wire as shown in **Fig. 6**; whereas, the A wire had a lower KAM value at the roll contact surface compared to the D wire. To quantitatively analyze the KAM behavior, the KAM values were compared with area and pass schedule as shown in **Fig. 11**. Overall, the D wire had more homogeneous KAM values with area than the A wire due to the more uniform distribution of effective strain during process. Therefore, it is apparent that the D pass schedule reduced the deviation of GND density with area, which is consistent with the results of effective strain and hardness.

3.3. Design Concepts for High Quality Flat-rolled Wire

Based on the experimental and numerical results achieved in the above comparative study, it is concluded that process parameters, such as height reduction per pass, roll diameter, and friction coefficient strongly affected the homogeneity and shape of the flat-rolled wire. Consequently, to make flat-rolled wire products with desired mechanical properties and shape, we needed to tailor the process conditions during the flat wire rolling process. To make a high quality flat-rolled wire product, a practical strategy was deduced as shown in **Fig. 12**. The homogeneity of flat-rolled wire increased with increasing total height reduction, and with decreasing height reduction per pass, roll diameter, and friction coefficient. Lateral spread of the flat-rolled wire increased with increasing total height reduction, roll diameter, friction coefficient, and height reduction per pass. Tailoring the height reduction per pass with the combination of low and high values was especially practical and useful toward obtaining higher quality flat-rolled wire products. It should be noted that the proposed practical strategy was valid for most metals because it was derived from the general plastic forming conditions. However, the magnitude of effect can be different with metal due to the different strain hardening rate and strain rate sensitivity with metal. For example, TWIP steels

Fig. 9. Comparison of measured (a) average hardness and (b) hardness profile along the horizontal and vertical directions of wires fabricated by the two pass schedules at the final pass. (Online version in color.)

Fig. 10. Comparison of IPF maps, IQ maps, and KAM maps of the flat-rolled wires processed by standard A pass and improved D pass schedules at the final pass. (Online version in color.)

Fig. 11. Comparison of KAM value of wire between standard A pass schedule and improved D pass schedule with area at the final pass. (Online version in color.)

have a higher strain hardening rate and a lower strain rate sensitivity compared to typical metals.²⁹⁾

Meanwhile, the proposed process condition, *i.e.*, the D pass schedule, was not perfectly optimized, meaning that the more optimization employed using the above design

Fig. 12. Schematic description showing the influence of process conditions on strain homogeneity and lateral spread of wire during the flat wire rolling process. (Online version in color.)

concepts, the better quality of flat-rolled wire. The proposed design concepts can provide process designers or engineers with sufficient data to choose the optimal process conditions

for high quality flat-rolled wire. This is highly beneficial for the industrial plants because roll gap control during the flat rolling process is easy to apply in the plant. Meanwhile, it should be noted that the effects of height reduction per pass and roll diameter should be considered to accurately predict b and W values of flat-rolled wire, *i.e.*, Eqs. (4) and (5) need to be modified considering the influences of height reduction per pass and roll diameter.

4. Conclusions

The influence of process conditions on the inhomogeneity of mechanical properties and shape change in TWIP steel wire was systematically studied during a flat rolling process. The major conclusions are as follows:

(1) It is necessary to consider the reduction in height per pass and roll diameter in order to make flat-rolled wire products with the proper homogeneity of mechanical properties and desired shape during the flat wire rolling process as such height has a large influence on strain inhomogeneity and lateral spread of flat-rolled wire. Strain inhomogeneity and lateral spread increased with increasing reduction in height per pass and roll diameter due to the higher length of the contact area. The underlying mechanism for the strain inhomogeneity and lateral spread of the flat-rolled wire was highly related to the length of the contact area. That is, the length of the contact area needs to be reduced by controlling the reduction in height per pass and roll diameter to improve the strain homogeneity of the flat-rolled wire.

(2) The effect of friction coefficient on the lateral spread is negligible, whereas strain inhomogeneity slightly increases with increasing friction coefficient.

(3) Based on the results of the parametric study using numerical simulation and experimental test, a new practical strategy was proposed for higher homogeneity of mechanical properties of flat-rolled wire: the combination of high and low reduction in height per pass improves the homogeneity of mechanical properties and microstructures with area of flat-rolled wire. This result should be greatly useful in the industrial field because roll gap control is easy to apply in the real plant during the flat rolling process. Considering productivity in a plant, it is also necessary to decrease the roll diameter for improving the strain homogeneity of flat-rolled wire.

Conflicts of Interest

The author declares no conflicts of interest.

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