Development of Width Spread Model for High Carbon Steel Wire Rods in Flat Rolling Process

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***Abstract*—High carbon steel wire rods rolled by flat rolling process are used to manufacture intermediate products of various shaped wires such as a saw blade, spring wire and piano wire. To achieve a desired geometry and dimensional accuracy, it is important to predict and control the width spread amount caused by the flat rolling. This study developed the width spread model for the high carbon steel wire in the flat rolling process by using the design of experiments (DOE) and FE analysis. The process variables considered in this study were the reduction of height, roll diameter, initial wire diameter and friction coefficient. The obtained FE analysis results were fitted to a second-order polynomial equation using multiple regression analysis. The spread formula was derived by solving the second-order polynomial equation. Finally, the width spread amount predicted using the proposed spread formula was compared with experiment results. The proposed width spread model led to a good agreement with the experimental results. Therefore, the proposed model can provide a valuable guideline for the prediction of wire width spread in the actual high carbon steel wire production.**

***Index Terms*—width spread model, flat rolling process, high carbon steel wire, DOE, FE analysis**

I. Introduction

Flattened wires are widely used to manufacture intermediate products of various shaped wires such as a saw blade, spring wire, piston ring and guide rail. In the flat rolling process depicted in Fig. 1, cold drawn wire is rolled between flat rolls for one or several passes to achieve the desired combination of thickness and width. Since the product is semi-manufactured, it is important to be able to control and predict the width spread in order to obtain the desired geometry for the customer [1]. In the flat rolling process, wire is placed on a three-dimensional deformation; thus, the plastic flow is considerably complex. In addition, numerous factors affect the width spread, such as the wire diameter, material, reduction of height, roll diameter, roll material and friction coefficient. Consequently, it is difficult to predict the width spread of the wire. Many researchers have attempted to consider all of these factors simultaneously to derive general formulas for the lateral spread. Wusatowski [2] proposed general empirical formulas considering the initial shape of the billet and the roll diameter to estimate the lateral spread of mild steel for practical rolling temperature ranges and plain sections. Shinokura et al. [3] proposed a new spread formula that considered geometrical variables and had only one coefficient. It had a high accuracy for every type of pass. Saito et al. [4] proposed general empirical formulas for various roll shapes such as square-oval, square-diamond and round-oval through experimental results from shape rolling. Kazeminezhad et al. [5] investigated the effects of the material properties and roll speed on the width of the contact area and width spread of rolled wire, and developed a theoretical relationship between the reduction in height and the width of the contact area of the wire. Recently, many researchers have used the FE analysis to investigate the deformation behavior of wire in the flat rolling process. Iankov [6] predicted the width spread of a final product using finite element simulation and compared the predictions with experimental results. Vallelano et al. [7] investigated the contact stress distributions prevailing in the roll-wire contact zone, as well as residual stresses in the resulting flat wire, as a function of the deformation inhomogeneity induced in the material. Kazeminezhad et al. [8] investigated the creation of macroscopic shear bands due to material flow tracks in the cross section of wire after flat rolling using the combined finite and slab element method. Shuai et al. [9] proposed spread model for TC4 alloy rod during the three-roll tandem rolling process. The diameter of inscribed circle of pass has an upmost effect on spread. Wang et al. [10] investigated the effect of nominal friction coefficients in spread formulas.

This study deal with the width spread of the high carbon steel wire in the flat rolling process by using the design of experiment (DOE) and FE analysis. The process variables considered in this study were the reduction of height, roll diameter, initial wire diameter and friction coefficient. We carried out FE simulations by developing reliable 3D-FE models using DEFORM

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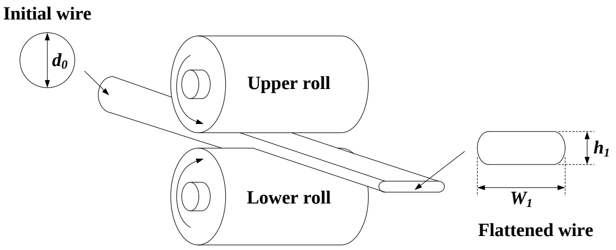


Figure 1. Schematic illustration of wire flat rolling process.

software, a commercially finite element platform. The obtained simulation results were fitted to a second-order polynomial equation using multiple regression analysis. The spread formula was derived by solving the second-order polynomial equation. Finally, the width spread amount predicted using the proposed spread formula was compared with experiment results. The proposed width spread model led to a good agreement with the experimental results. Therefore, the proposed model can provide a valuable guideline for the prediction of wire width spread in the actual high carbon steel wire production.

II. Spread Formula for Wire Flat Rolilng Process

The parameter that was analyzed for the flat rolling process was the width spread of the wire, i.e., the difference between the initial width and the maximum width of the wire after the flat rolling process. The mean vertical stress between the rolls and strip can be defined as the normal pressure *s*, corresponding to a lateral compressive stress of *ms*, where m is a function of the geometry of the plastic zone, rolling temperature and composition. The value of *m* lies between that of plane strain and plane stress deformation condition, i.e. $0 \le m \le 0.5$. Neglecting the stress in the longitudinal direction, then from the Levy-Mises plastic stress-strain relations, we have [11]:

$$\frac{\ln\left(W_1/W_0\right)}{\ln\left(h_0/h_1\right)} = p \text{ or } \frac{W_1}{W_0} = \left(\frac{h_0}{h_1}\right)^p, \left(0 \le p \le \frac{1}{2}\right) \quad (1)$$

where W_0, W_1, h_0 and h_1 are the initial width, final width, initial height and final height of strip, respectively.
Wusatowski proposed the following relationship for the spread in the strip rolling process [11,12].

$$\frac{W_1}{W_0} = a'b'c'd'\left(\frac{h_0}{h_1}\right)^p \quad (2)$$

where *p* is a function of the roll diameter and the ratio of the initial width to the height of the strip. The variables *a'*, *b'*, *c'* and *d'* are correction factors that differ slightly from unity and allow for variations in the steel composition, rolling temperature, rolling speed, and roll material, respectively. Equation (2) is similar to Eq. (1), which was derived from the experimental results. The difference between Eq. (1) and (2) is due to the existence of stress in the longitudinal direction.

To develop a width spread formula for the flat rolling of wire rods, $W_0 = h_0 = d_0$ is assumed, where d_0 is the initial wire diameter. Because Eq. (2) has five correction factors, it is inconvenient to use in industry because numerous experiments are required to determine them. In this study, the correction factors in Eq. (2) were simplified using two correction factors, *A* and *p*, for the wire flat rolling process, as follows:

$$W_1 = AW_0\left(\frac{h_0}{h_1}\right)^p \quad (3)$$

where *A* and *p* are correction factors for the flat rolling of wire rods. For the calculation of the width spread of wire rods using the above equation, it is necessary to determine the correction factors of the spread formula.

III. Prediction Method of Width Spread Amount for Flat Rolling of Wire Rods

A. Procedure for Prediction of Width Spread

To develop a spread formula for the flat rolling of wire rods, the DOE and FE analysis were carried out. The prediction procedure is summarized as follows:

Step 1. Set process variables: The process variables were determined as d0, dR, μ and Δh/h0, i.e., the initial wire diameter, roll diameter, friction coefficient and reduction of height, respectively.

Step 2. Design of experiments: A Box-Behnken design was carried out using the selected variables to decide FE analysis cases.

Step 3. Conduct FE analysis: FE analysis was performed to predict the width spread amount of the rolled wire rods using DEFORM.

Step 4. Calculate width spread using second-order polynomial equation: The width spread of the rolled wire rods was calculated using a second-order polynomial equation by substituting the process variables selected in Step 1.

Step 5. Plot W_1/W_0 with respect to h_0/h_1: Using the calculated data from Step 4, W_1/W_0 was plotted with respect to h_0/h_1.

Step 6. Plot $log(W_1/W_0)$ with respect to $log(h_0/h_1)$: In order to extract the correction factors (*A*, *p*), $log(W_1/W_0)$ was plotted with respect to $log(h_0/h_1)$.

Step 7. Extract correction factors (*A*, *p*): Using the graph of $log(W_1/W_0)$ versus $log(h_0/h_1)$, the correction factors (*A*, *p*) were extracted by a linear equation.

Step 8. Predict width spread using spread formula: The width spread of the wire rods in flat rolling process was predicted by the spread formula derived in Step 7 by substituting W_0 and h_0/h_1.

B. Design of Experiments

The Box-Behnken design model was used to determine the process variables for the width spread of the wire rods, such as the reduction of height, wire diameter, roll diameter and friction coefficient between the rolls and wire. The number of computational experiments needed to obtain a response such as the width spread can be

TABLE I. PROCESS VARIABLES IN BOX-BEHNKEN DESIGN MODEL

Variables	Factors	Level Low	Level Middle	Level High
Reduction of height ($\Delta h/h_0$)	X_1	14%	17%	20%
Roll diameter (d_R)	X_2	240 mm	280 mm	320 mm
Wire diameter (d_0)	X_3	5 mm	6 mm	7 mm
Friction coefficient (μ)	X_4	0.09	0.12	0.15

TABLE II. CHEMICAL COMPOSITIONS OF HIGH CARBONE STEEL WIRE

Compositions	C	Si	Mn	P	S	Cu
wt.%	0.59 ~0.66	0.15 ~0.35	0.60 ~0.90	0.003	0.030	0.030

TABLE III. MECHANICAL PROPERTIES OF HIGH CARBON STEEL WIRE

Yield stress (Y.S.)	Ultimate tensile stress (U.T.S.)	Strength coefficient (K)	Work-hardening exponent (n)
663 MPa	1056 MPa	1847.6 MPa	0.1852

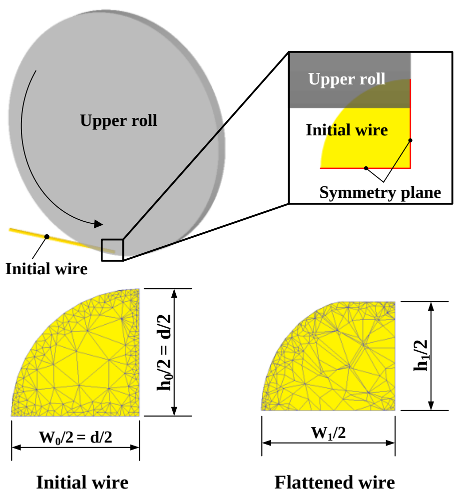


Figure 2. FE model for wire flat rolling process.

reduced. We used four variables; thus, the number of experiments was decreased from 4^3 = 64 (for the full factorial design) to 27 with the Box-Behnken design. The four variables and three levels of the Box-Behnken design model are presented as shown in Table I.

Including four independent variables (X_1, X_2, X_3 and X_4), the mathematical relationship of the responses for these variables can be expressed by the second-order polynomial regression equation.

$$Y = \beta_0 + \sum \beta_i X_i + \sum \beta_{ii} X_{ii}^2 + \sum \beta_{ij} X_i X_j \qquad (4)$$

where β_0 is the offset term, β_i is the slope or linear effect of the input factor X_i, β_{ii} is the quadratic effect of the input factor X_i, and β_{ij} is the linear-by-linear interaction effect between the input factors X_i and X_j.

C. FE Analysis

To obtain the width spread amount of the wire rods, we carried out FE simulations by developing reliable 3D-FE models using DEFORM software, a commercially finite element platform. The chemical composition of the high carbon steel wire rods used in this study is shown in Table II. The mechanical properties were obtained through a tensile test, as shown in Table III.

Fig. 2 shows an FE model for the flat rolling of wire rod. Both the rolls and wire were modeled for only 1/4 of the entire geometry, owing to the double symmetry in both the geometrical and load terms. Thus, the computational time was reduced considerably. The nodes of the sections influenced by the symmetries were constrained to represent the symmetries correctly.

A total of 27 FE analysis cases were performed, as shown in Table IV. According to FE analysis results, which are depicted in Fig. 3, h_1 and W_1 were measured. The magnitude of the width spread after the flat rolling process was obtained by the following equation (5).

$$\Delta W = W_1 - d_0 \qquad (5)$$

where ΔW is difference between the initial diameter and the final width of the rolled wire.

The width spreads obtained from FE analysis were used to formulate a second-order polynomial equation. A mathematical equation representing the lateral spread of the wire is given by Eq. (6).

$$\begin{aligned}\Delta W = {} & 0.48 - 0.027X_1 - 1.9\cdot10^{-3}X_2 - 0.035X_3 \\ & - 0.506X_4 + 7.22\cdot10^{-4}X_1^2 + 2.97\cdot10^{-6}X_2^2 \\ & - 1.25\cdot10^{-3}X_3^2 + 8.71\cdot10^{-15}X_4^2 \\ & + 1.67\cdot10^{-5}X_1X_2 + 5.167\cdot10^{-3}X_1X_3 \\ & + 5.556\cdot10^{-3}X_1X_4 + 1.25\cdot10^{-5}X_2X_3 \\ & + 8.33\cdot10^{-4}X_2X_4 + 0.05X_3X_4\end{aligned} \qquad (6)$$

TABLE IV. MECHANICAL PROPERTIES OF HIGH CARBON STEEL WIRE RODS

No. of case	$\Delta h/h_0$ (%)	d_R (mm)	d_0 (mm)	μ	ΔW (mm)
1	17	320	6	0.09	0.338
2	17	280	6	0.12	0.328
3	17	240	7	0.12	0.368
4	17	280	7	0.09	0.370
5	17	240	6	0.15	0.326
6	20	280	5	0.12	0.376
7	20	320	6	0.12	0.454
8	17	280	6	0.12	0.328
9	14	280	6	0.15	0.236
10	20	280	6	0.09	0.432
11	17	320	6	0.15	0.348
12	17	240	5	0.12	0.274
13	20	280	6	0.15	0.438
14	17	280	7	0.15	0.382
15	17	280	5	0.09	0.274
16	17	320	5	0.12	0.294
17	17	240	6	0.09	0.320
18	20	280	7	0.12	0.496
19	20	240	6	0.12	0.428
20	17	280	5	0.15	0.280
21	17	320	7	0.12	0.390
22	14	280	7	0.12	0.260
23	14	280	5	0.12	0.202
24	14	280	6	0.09	0.232
25	14	240	6	0.12	0.228
26	17	280	6	0.12	0.328
27	14	320	6	0.12	0.338

where ΔW is difference between the initial diameter and the final width of the wire, and X_1, X_2, X_3 and X_4 are the reduction of height, roll diameter, wire diameter, and friction coefficient between the rolls and wire, respectively.

The fitting model was evaluated according to the correlation coefficient (R^2) between the FE analysis results and the values of the response variable predicted using the model, as shown in Fig. 3. The R^2-value was 0.99, which showed that the deviation between the FE analysis results and the mathematical model was small. Therefore, the mathematical model for the width spread agreed well with the FE analysis.

To develop a width spread formula for the wire flat rolling process, the second-order polynomial Eq. (6) was modified by Eq. (3). The selected process variables are shown in Table V.

Then width spread of the wire was calculated by the second-order polynomial Eq. (6). Using the calculated data, W_1/W_0 was plotted with respect to h_0/h_1, as shown in Fig. 4. To extract the correction factors, $log(W_1/W_0)$ was plotted with respect to $log(h_0/h_1)$, as shown in Fig. 5. According to the linear relationship between $log(W_1/W_0)$ and $log(h_0/h_1)$, the correction factors A and p were determined to be 0.9720 and 0.4498, respectively, and the spread formula was obtained, as shown in Eq. (7).

$$\frac{W_1}{W_0} = 0.9720\left(\frac{h_0}{h_1}\right)^{0.4498} \tag{7}$$

The width spread of rolled wire rods can be predicted easily using Eq. (7), by substituting W_0 and h_0/h_1.

IV. Experimental Verification

Experimental tests were conducted to verify the effectiveness of the spread formula. Table VI shows the experiment case of the flat rolling of wire. A rolling machine with two cylindrical rolls 320 mm in diameter was used for the flat rolling of wire. High carbon steel wire rod was used, and the initial wire diameter was 6.3 mm. The wire was drawn from a 10 mm wire rod manufactured by hot rolling. The friction coefficient between the rolls and wire is approximately 0.1~0.15 when lubrication is applied at room temperature. A commercial lubricant was applied at the inlet and outlet of the rolling machine. The reduction of height was 14, 17, and 20%, respectively.

Fig. 6 shows the cross sections of the flattened wire obtained from the experiment. According to the experimental results, the maximum width of the wire increased with the increase in the reduction of height. The FE analysis results, the predicted results, and the experimental results for the maximum width of the wire are compared in Table VII.

TABLE V. Selected Process Variables for Spread Formula

Reduction of height ($\Delta h/h_0$)	Roll diameter (d_R)	Wire diameter (d_0)	Friction coefficient (μ)
14~20%	320 mm	6.3 mm	0.12

TABLE VI. Experimental Conditions for Verification

No. of case	Wire diameter (d_0)	Roll diameter (d_R)	Reduction of height ($\Delta h/h_0$)
1	6.3 mm	320 mm	14%
2			17%
3			20%

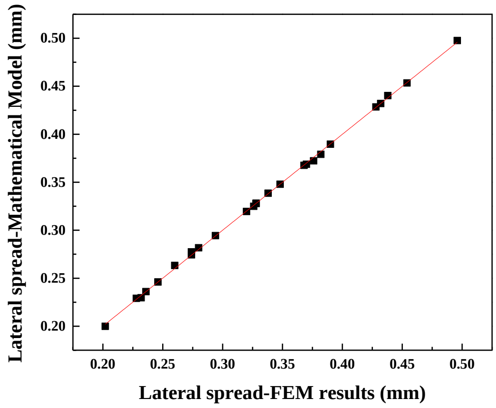


Figure 3. Relationship between FEM results and mathematical model.

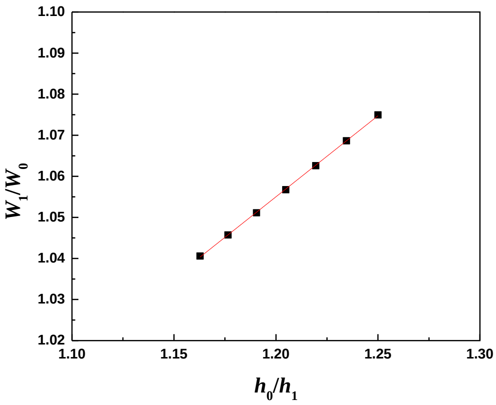


Figure 4. Relationship between W_1/W_0 and h_0/h_1.

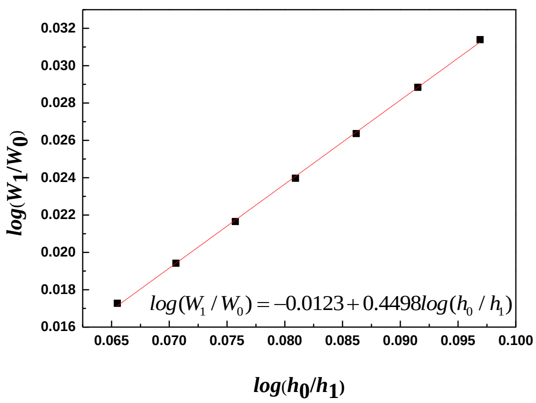
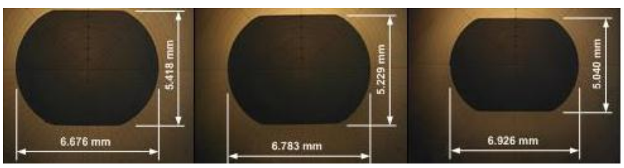


Figure 5. Relationship between $log(W_1/W_0)$ and $log(h_0/h_1)$.



(a) Case 1 (b) Case 2 (c) Case 3

Figure 6. Cross-sectional shapes of flat rolled wire rods.

TABLE VII. COMPARISON OF EXPERIMENTAL, SPREAD FORMULA AND FE ANALYSIS RESULTS

No. of case	Width of flattened wire (mm)		
	Experiment	Spread formula	FE analysis
1	6.676	6.552 (-1.9 %)	6.554 (-1.8 %)
2	6.783	6.657 (-1.9 %)	6.658 (-1.8 %)
3	6.926	6.768 (-2.3 %)	6.778 (-2.1 %)

The FE analysis and spread formula results are fairly similar but differ from the experimental results. The experimental values are larger than both the spread formula and the FE analysis values, with a maximum error of 2.3%. Several reasons for this difference are suggested. The friction between the wire and rolls and the temperature caused by plastic deformation heat did not exhibit a significant influence, but this error was due to the mechanical anisotropy of the wire and the insufficient material model [13]. In this study, the mechanical anisotropy of wire was not considered, because an isotropy model was used in the FE simulation. For more exact predictions, it is necessary to consider the mechanical anisotropy of the drawn wire and use a more sophisticated material model.

V. CONCLUSIONS

In this study, the prediction model of width spread for high carbon steel wire rods in flat rolling process based on the DOE and FE analysis. Furthermore, the proposed spread formula was validated through FE analysis and experimental results. The main conclusions are as follows:

(1) A spread formula for the flat rolling of wire rods was developed by modifying the spread formula for the flat rolling of strips. The number of correction factors in the spread formula was reduced from five (a', b', c', d', p) to two (A, p) for simplicity.

(2) FE analysis was performed using DEFORM-3D in order to estimate the width spread amount. And after, a second-order polynomial equation was derived using the FE analysis results. The correction factors A and p were determined to be 0.9720 and 0.4498, respectively, as shown in Eq. (7).

(3) The proposed width spread model led to the high dimensional precision. This research results provide a valuable guideline for the prediction of wire width spread in actual high carbon steel wire production.

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