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Developing a Two-roll Wire Straightener

Wei-chen Lee, *Member, IEEE*, and Kun-Chung Huang

***Abstract*—Wire straightening is essential for obtaining a piece of straight wire from a roll of wire stock. The objectives of this research were to develop a two-roll wire straightener and find the appropriate roll gap and roll angle for the straightener based on the finite element analysis results. A PLC was employed as the main controller to control motors that adjust the parameters. An image acquisition and processing unit were also built to obtain the deformation of the aluminum wire offline. The wire used in the study is a 1050 series aluminum wire with a length of 400 mm and a diameter of 2.98 mm. Three wires were analyzed with initial deformations of 5.0 mm, 7.5 mm, and 10.0 mm. Full factorial experiments of the straightening process were simulated using the finite element analysis. Then, a two-way analysis of variance was performed on experimental data. Subsequently, the straightening parameters with the smallest residual deformation were adopted as the optimal parameters for the wire straightener. Using the parameters found in this study can improve the residual deformation by over 90%.**

I. Introduction

Forming a three-dimensional metal component such as a screw propeller [1] is extremely complicated. Wire straightening is a good starting point in studying how to control the deformation of a three-dimensional component. Many researchers have studied the parameters of cross-roll straightening machines and discussed the factors that may affect various straighteners' performance, such as the throughput speed and the degree of straightness [2]. However, ideal assumptions often lead to situations where the straightening accuracy cannot meet expectations. In recent years, some researchers have continuously proposed different methods to determine the straightening parameters for better performance. The methods can be divided into four major categories, including elastic-plastic theory, finite element analysis, experiments, and neural networks, as shown in Fig. 1.

Using the elastic-plastic theory, Wu et al. [3] modeled the straightening process of a two-roll straightening machine as a successive process of the multiple reverse bending of a bar. They claimed that the curvature of every bending of the bar should depend on the curvature of the gap between two rolls. Wu et al. [3] first derived the relationship between the bar's speed and the roll's angle, then analyzed the roll gap curvature on the curvature of the straightened bar. They also considered the curvature caused by the spring-back and derived it based on the elastic strain energy, thereby obtaining the relationship of the final curvature of the bar after straightening. On the other hand, Wang et al. [4] derived the theoretical straightening moment and applied it to the arc-welding pipes using a three-roll straightener. They demonstrated that the straightness of the straightened pipes could be controlled within 1.5% using the method.

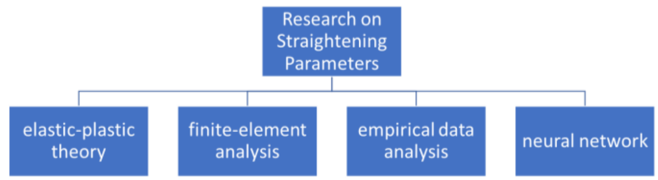

Figure 1. The main approaches were used to study the parameters of straighteners.

Since wire straightening involves the mechanical properties of the material itself and the parameters of the straightening machine, it is a sophisticated process. A theoretical calculation cannot fully reflect the real situation, prompting several researchers to adopt finite element methods (FEM) to model the straightening process and simulate the effects of various straightening parameters. Mutrux et al. [5] used LS-DYNA, an explicit finite element analysis software, to simulate the straightening results of a two-roll straightener. The simulated yield stresses under different strengthening conditions were consistent with the test results. Meanwhile, Flipon et al. [6] used a different nonlinear finite element software, Metafor, to model a two-roll round bar straightener. Their results showed that it is promising to use the simulation to study the key parameters in the straightening process. Moreover, Ma et al. [7] developed a continuous variable curvature roll shape for a two-roll straightener and used finite element software ABAQUS to perform simulation for validation.

It is common to use experimental or empirical data to determine straightening parameters. For example, Hong et al. [8] installed a force sensor and a displacement sensor on their straightening machine to obtain the relationship between the load exerted by the indenter and the deflection of the guide rail. Then, they used the experimental data to determine the stroke of their straightening machine. A few researchers have recently adopted deep learning techniques to train models for predicting straightening parameters. Yi et al. [9] used an artificial neural network (ANN) to control their straightening machine for shafts. The neural network architecture consists of an input layer with six inputs, several hidden layers, and an output layer with two outputs. They collected the deformation at five locations of the shaft to find the location of the largest deformation and used the found location as the bending point. Then, the stroke was determined by the ANN model. Some other approaches were also used for straightening materials. Halama et al. [10] used eight cameras to catch the image and define the shape of a steel billet. Then, the shapes were classified into four different types, each corresponding to a different straightening algorithm.

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W. C. Lee is with the Department of Mechanical Engineering, National Taiwan University of Science and Technology, Taipei, 106335, Taiwan, (phone: 886-2-2737-6478; fax: 886-2-2737-6464; e-mail: wclee@ mail.ntust.edu.tw).

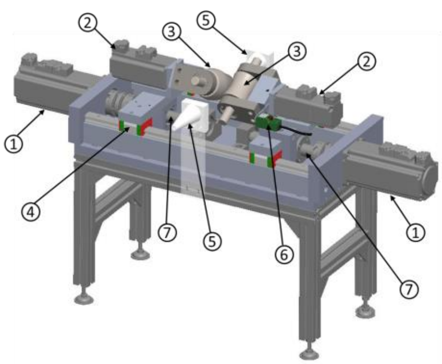
K. C. Huang is with the Department of Mechanical Engineering, National Taiwan University of Science and Technology, Taipei, 106335, Taiwan, (e-mail: dacid321321@gmail.com).

Furthermore, many researchers focused on studying the parameters of the straightener rather than the design of the straightener itself. However, to investigate the parameters, a straightener is first required. The objective of this research was to build a two-roll wire straightener. Based on the straightener, the straightener's behavior was simulated using the finite element method to determine its parameters, including the roll angle and the roll gap.

II. Materials and Methods

A. Two-Roll Straightener

In this research, we developed a cross-roll wire straightener. The wire is straightened in the straightener, passing through the two rolls in such a way that it rotates about its own longitudinal axis. In other words, the wire is in a spiral motion during the straightening process and is subjected to bending in all possible directions to achieve straightness. The design of the straightener is shown in Fig. 2. We used four servo motors to precisely control the gap and angle of the rolls, and also to keep the straightening operation in the middle so that the wire can be fed at a fixed position. Two motors used for adjusting the roll angle were 100 W servo motors (ECMA-C10401QS, Delta, Taiwan), as shown in Fig. 3, and the other two for adjusting the position of the roll or roll gap through the screws were 200 W servo motors (ECMA-C10602CS, Delta, Taiwan), as shown in Fig. 4. In addition, the two motors used in this study, which drive the two rolls to spin, were 90 W single-phase reversible gear motors (5RK90GE-AW2L2, Oriental Motor, Japan). The two motors could provide about 13.9 N-m rated torque each to the rolls during the straightening process. The proximity switches (SN04-N2, ROKO, Taiwan) shown in Fig. 2 were used to locate the home positions because we used incremental encoders in the servo motors.



number	part
1	200W servo motor
2	100W servo motor
3	roll
4	linear guideway
5	wire entry/exit
6	proximity switch
7	screw

Figure 2. The design of the two-roll wire straightener and its major components (two reversible motors connected to the two shafts of the rolls are not shown for clarity)

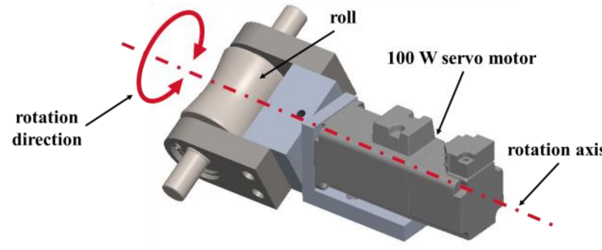


Figure 3. The 100 W servo motor is used to control the roll angle.

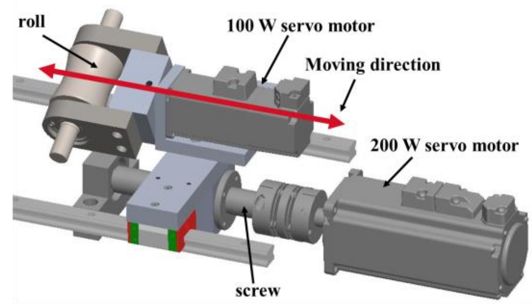


Figure 4. The 200 W servo motor controls the roll gap, the distance between two rolls, through a screw.

Fig. 5 shows the control system architecture of the straightener. The six motors of the straightener were controlled by a PLC (FX5U with transistor output, Mitsubishi, Japan). The reversible motors can be turned on or off using relays, and the servo motors were controlled by sending pulses from the PLC to the motors' drivers. In this study, an HMI (DOP-B08E515, Delta Taiwan) was connected to the PLC through the Modbus RTU protocol. An image acquisition and processing unit consisting of a PC and an industrial camera were used to obtain the wire's deformation offline. Then, the information was passed to the PLC for automatically setting up the roll gap and roll angle of the straightener.

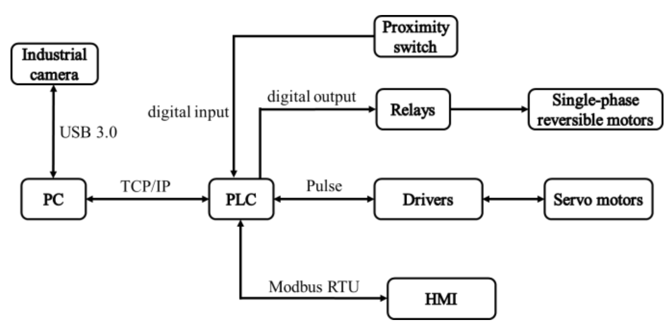


Figure 5. The control system architecture of the straightener.

For a two-roll straightener, the rolls are considered critical components. The two rolls include a convex roll and a concave roll processing at an oblique angle. In operation, the two rolls rotate in the same direction, with the wire rotating along the rolls gap in the reverse direction of the rolls by the friction of the rolls. During the straightening process, the wire is subject to continuous bending. Among the several roll designs proposed in the literature, we adopted the three-curvature roll design, as shown in Fig. 6, proposed by Cui [11]. As the name implies, the roll has three different curvatures, which can straighten the wire in three stages. The shape of the roll in

Section 1 makes the wire subject large and uniform bending deformation, which creates uniform residual deformation. Section 2 is used to eliminate the residual deformation, and Section 3 is to improve the straightness of the wire. As shown in Fig. 6, each section has its own curvature, and the rolls are symmetrical. Following the guidelines in [11], we calculated the design parameters for the rolls, as listed in Table 1.

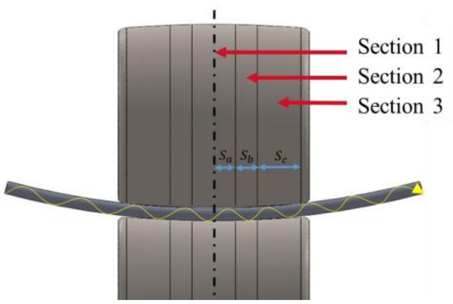


Figure 6. The three sections of the roll design.

TABLE I. DESIGN PARAMETERS OF THE ROLLS

Section	Length (mm)	Radius of curvature (mm)
1	5.25	153
2	5.25	460
3	10.50	537

B. *Image Acquisition and Processing Unit*

To obtain the deformation of the aluminum wire, we built an image acquisition and processing unit, which includes a PC and a 5-million-pixel black-and-white industrial camera (acA2500-14uc, Basler, Germany). Placing a backlight under the aluminum wire can make the edge contour of the aluminum wire clearer. We used LabVIEW as the image processing software. The image processing flow is as follows: The original image was binarized first. Then, a morphological opening operation was employed to smooth the contour edge. Subsequently, contour edge detection was performed to obtain the two outer edges of the aluminum wire, the edges were averaged to obtain the center line of the aluminum wire, and the center line was fitted to a quadratic curve. Finally, a straight line connecting the curve's ends was created to find the maximum deformation of the curve, as shown in Fig. 7. In addition to obtaining the initial deformation before straightening, the image acquisition and processing unit was used to obtain the residual deformation after straightening the aluminum wire.

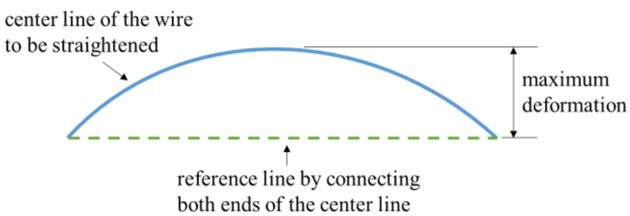


Figure 7. The maximum deformation obtained from the image acquisition and processing unit

C. *Finite Element Analysis (FEA) with Design of Experiments (DOE)*

This study used finite element analysis software for simulating the straightening process. Although aluminum wires of 400 mm were used in the experiment, the aluminum wire of 20 mm was simulated to reduce the computation time, a common practice in the industry. The wire material for straightening in this research is 1050 aluminum alloy. Its mechanical properties are shown in Table 2. The bilinear hardening material model was used in the simulation.

TABLE II. MECHANICAL PROPERTIES OF 1050 ALUMINUM ALLOY USED IN THE SIMULATION

Young's modulus	Poisson's ratio	Yield strength	Tangent modulus
69 GPa	0.32	90 MPa	31.5 GPa

We designed a two-factor full-factorial experiment in simulation to find the optimal parameters that can be used with our straightener. The two factors were the roll angle and roll gap. The roll angle α is the angle between the rolls and the center line of the wire, as shown in Fig. 8; the roll gap is the minimum distance between the surfaces of the two rolls. The roll angle was used in our roll design to facilitate the aluminum wire to be engaged into the two rolls; the roll gap controlled the maximum bending of the wire during the straightening process. Both are important factors for our roll design. The levels of each factor are shown in Table 3. There are five levels for the roll angle and four levels for the roll gap, as indicated in Table 3. The minimum value of the roll angle used in the DOE was set to 16° because it was found during the actual straightening process that the roll would not bite into the wire if the angle was less than 16°. The maximum value of the roll angle was 20° because the straightening effect would gradually deteriorate due to the lack of enough numbers of bending when the angle was greater than 20°. The minimum value of the roll gap was 2.98 mm, equivalent to the aluminum wire's diameter. The maximum value of the roll gap was 3.04 mm. The straightening effect was unsatisfactory when the spacing was greater than 3.04 mm. We repeated each trial once, so there were 40 data for each of the three aluminum wires with different initial deformations, which are 5.0, 7.5, and 10.0 mm, respectively. In the repeated trial, we increased the roll angle of each model by 0.001° to simulate the noises or errors usually found in actual experiments.

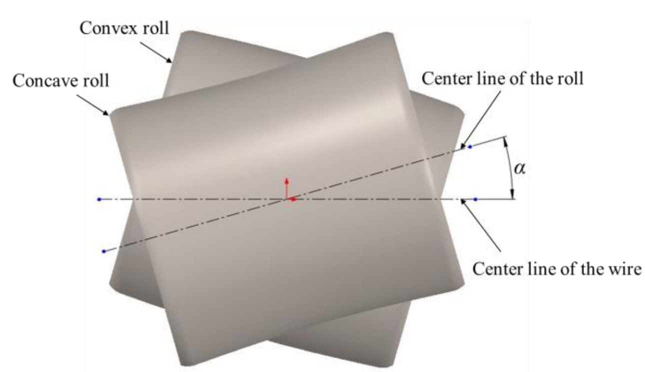


Figure 8. The roll angle α is the skew between the roll and the aluminum wire's center line.

TABLE III. THE FACTORS AND THEIR LEVELS IN THE DOE.

Factors	Levels
Roll angle	16°, 17°, 18°, 19°, 20°,
Roll gap	2.98, 3.00, 3.02, 3.04

To quantify the straightening effect, we used the MATLAB built-in function, polyfit, to fit the nodes along the center line of the straightened aluminum wire model to a quadratic curve and then calculated the curvature of the curve. The curvature allowed us to calculate the residual deformation based on the wire length of 400 mm.

III. RESULTS AND DISCUSSION

The completed two-roll wire straightener developed in this research is shown in Fig. 9, in which we can see that two reversible motors drive the two rolls using two universal joints. Fig. 10, the enlarged view of Fig. 9, shows how a wire passes through the wire entry, two rolls, and the wire exit to get straightened. The wire straightener functioned well, allowing us to perform the wire straightening experiments. The automation control panel was placed beside the straightener. As shown in Fig. 11, the panel consists of the PLC, four drivers for the four servo motors, two capacitors for starting the reversible motors, a 24 V power supply, and the power switches. Before performing the experiments, we simulated the process to obtain the parameters we needed for the straightener.

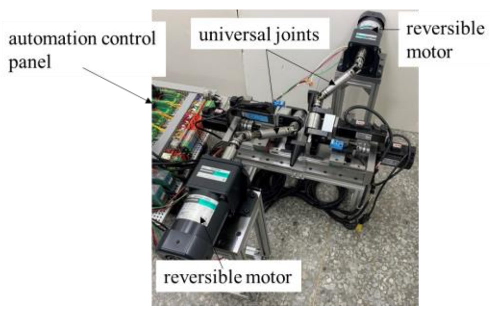


Figure 9. The completed two-roll wire straightener developed in this research.

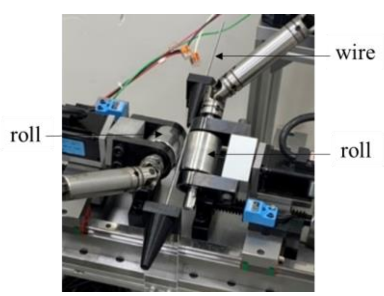


Figure 10. The enlarged view of Fig. 9 to show how a wire passes through the mechanism to get straightened.

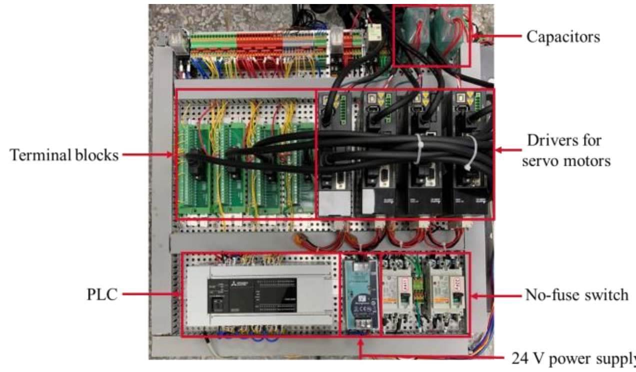


Figure 11. The automation control panel consists of a PLC, a 24 V power supply, capacitors, switches, and four drivers for servo motors.

We performed a finite element analysis on the straightening models with the initial deformation of aluminum wires of 5.0 mm, 7.5 mm, and 10.0 mm, respectively. Because the procedures are the same for the wires with different initial deformation, we used the wire of 5 mm initial deformation as an example here for discussion. After obtaining 40 simulation data, we performed an analysis of variance (ANOVA) to determine the significance of the factors. Because this experiment had two control factors, a two-way ANOVA was performed. The ANOVA table is listed in Table 4, and the significance level was set at 5%. Table 4 shows that the p-values of the two factors and their interaction are far less than the significance level, so the two factors and their interaction are all significant.

TABLE IV. ANALYSIS OF VARIANCE TABLE

source of variation	sum of square	degrees of freedom	p-value
Roll gap	19.73	3	1.35×10^{-16}
Roll angle	34.95	4	1.46×10^{-18}
interaction	7.98	12	5.28×10^{-10}
error	0.46	20	
sum	63.12	39	

After determining the significance of the factors and the interaction, we then built the regression model as (1), where x_1 is the roll gap, x_2 is the roll angle, x_1x_2 is the interaction, ε represents the regression residual, and the beta coefficients (β_0, β_1, β_2, β_3) are the slopes of the corresponding variables or interaction.

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_1 x_2 + \varepsilon \quad (1)$$

We used MATLAB's Statistics and Machine Learning Toolbox to build the model. The beta coefficients of the model were obtained using the function regress, and the model was plotted in the mesh form, as shown in Fig. 12. The blue dots in Fig. 12 are the experimental data, and some of the dots cannot be seen due to the mesh. The regression statistics of the model are listed in Table 5. The R squared of this model was 0.9032, and the p-value of the model was far less than the significance level of 0.05, which means that the model fits the data well.

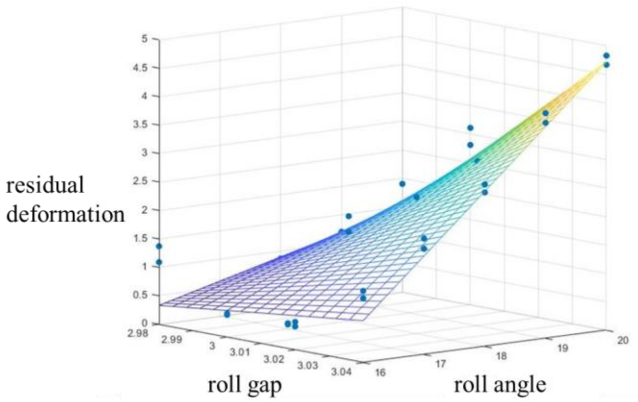


Figure 12. The regression model in the mesh form and the data used for obtaining the model

TABLE V. REGRESSION STATISTICS

R squared	0.9032
F value	111.99
p-value	2.59×10^{-18}
Mean square error	0.17

Using the same procedure discussed previously, we analyzed the other two different aluminum wires with initial deformations of 7.5 mm and 10.0 mm, respectively. Then, based on ANOVA, we determined the optimal parameters for the straightener, as listed in Table 6. The table shows that the optimal straightening parameters for the initial deformations of 5.0 mm and 7.5 mm aluminum wire are the same: roll gap (2.98 mm) and roll angle (17°). For the wire with an initial deformation of 10.0 mm, the roll gap should be set at 3.00 mm and the roll angle at 16°. Furthermore, the actual straightening experiments of the aluminum wires were performed, and the simulation and actual straightening results were compared, as listed in Table 7. It can be observed that the residual deformation of the 400-mm aluminum wires with initial deformations of 5.0 mm and 7.5 mm could be controlled within 0.5 mm after actual straightening, and those with initial deformation of 10.0 mm could be controlled within 0.1 mm after actual straightening. This finding means that more than 90% of the deformation can be improved for all three wires. In addition, the absolute errors between the simulated deformations and the actual residual deformations were within 0.1 mm.

TABLE VI. OPTIMAL STRAIGHTENING PARAMETERS OBTAINED FROM FEA AND ANOVA FOR THE THREE ALUMINUM WIRES

initial deformation (mm)	**Roll gap (mm)**	**Roll angle (°)**
5.0	2.98	17
7.5	2.98	17
10.0	3.00	16

TABLE VII. COMPARISON OF THE SIMULATION RESULTS AND ACTUAL RESULTS FOR THE THREE ALUMINUM WIRES

Initial deformation (mm)	**Simulated residual deformation (mm)**	**Actual residual deformation (mm)**	**Absolute error(mm)**
5.0	0.425	0.480	0.055
7.5	0.485	0.400	0.085
10.0	0.190	0.090	0.100

Table 6 shows that the straightening parameters are the same for the aluminum wires with initial deformations of 5.0 mm and 7.5 mm. It was assumed that aluminum wires with an initial deformation between 5.0 to 7.5 mm could also adopt the same parameters of 2.98 mm and 17°. To verify this assumption, we conducted experiments with three different aluminum wires: one with an initial deformation of 6.0 mm, one with an initial deformation of 7.0 mm, and an S-shaped aluminum wires with deformations of 5.0 and 7.5 mm at different locations. We used the roll gap of 2.98 mm and the roll angle of 17° for straightening. The aluminum wires before and after straightening are shown in Fig. 13. Table 8 lists the residual deformations after straightening, which were all within 0.4 mm. Based on the results, the parameters of the roll gap of 2.98 mm and the roll angle of 17 ° can be used for straightening aluminum wires with initial deformations between 5.0 to 7.5 mm. During a complete straightening process, the wire rotated about eight revolutions.

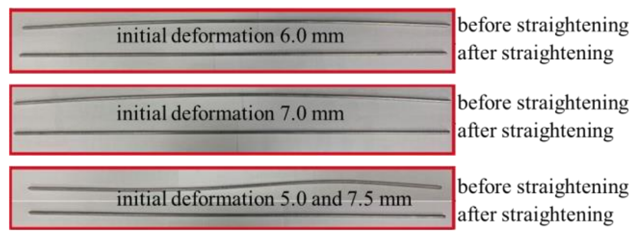


Figure 13. Three aluminum wires of initial deformation between 5.0 mm and 7.5 mm before and after straightening

TABLE VIII. RESIDUAL DEFORMATION OF THE THREE ALUMINUM WIRES OF INITIAL DEFORMATION BETWEEN 5.0 MM AND 7.5 MM

Initial deformation (mm)	**Residual deformation (mm)**
6.0	0.36
7.0	0.22
S shape	0.31

IV. CONCLUSION

This research developed a two-roll wire straightener. Using the finite element analysis and ANOVA, the appropriate straightening parameters for the straightener were obtained. The studies demonstrated that the proposed method could reduce the deformations of the 1050 aluminum wires with initial deformations of 5.0 mm, 7.5 mm, and 10.0 mm by more than 90%. The future work for the study will involve integrating the image acquisition and processing unit with the straightening machine for online inspection We will also perform a full-factorial experiment on the straightener to build up a more realistic look-up table to automate the straightening process.

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