OPTIMIZATION OF A ROLLER LEVELLING PROCESS FOR AL7001T9 PIPES WITH FINITE ELEMENT ANALYSIS AND TAGUCHI METHOD

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Summary

This paper is concerned with optimization of process parameters for a roller leveller that is an indispensable equipment to eliminate the undesirable curvature of a thin-walled aluminum pipe. Optimization of process parameters has been carried out for a multi-staggered-type 14-roller leveller. A finite element model of a multi-staggered 14-roller leveller was constructed for analysis whose results were verified by experiments. The analysis is carried out with the fractional model and the Taguchi method for evaluation of the effect of process parameters such as the intermesh and the slanted angle of rollers. The response variable is set to the plastic strain along the pipe length. The optimum combination of process parameters is determined from the numerical result and confirmed by experiments. The comparison of the numerical result with the experimental one shows good coincidence for its validity and reliability.

Keywords: Roller levelling; Intermesh; Slanted angle; Elasto-plastic finite element analysis; Taguchi method, SN (Signal-to-Noise) ratio, ANOVA (ANalysis Of VAriance)

1 Introduction

Thin-walled aluminum pipes are used for arrows or sports tent poles. The strength of tent poles is the most competitive issue for the sports tent makers since the world market of sports tent demands lighter and stronger tent poles persistently. Enhancement of the strength of the pipe often requires additional tube-drawings and heat treatments. No matter how precise the manufacturing system of pipes is, the pipe after various process histories has residual strains and stresses with the undesirable curvature in itself. The curvature of a pipe is one of the most important factors in determining the quality of the pipe and can be eliminated by a roller levelling process. A roller leveller consists of several pairs of rotating staggered rollers in which a pipe to be straightened is inserted for serial bending and unbending during the leveling process.

Al7001T9 is a good candidate to enhance the strength of a pipe as a substitution for Al7001T6. Al7001T9 has the yield stress of 663MPa and the elongation of 2%, while Al7001T6 has the yield stress of 550MPa and the elongation of 12%. Because of the mechanical properties of the high yield stress and the very small elongation of

Al7001T9, it is extremely difficult to straighten the pipe with existing roller levellers designed for the Al7001T6 pipe. The difficulties have to be overcome with identification of the levelling mechanism as well as the critical process parameters such as the intermesh of each roller and the slanted angle of rollers. The roller levelling process of an Al7001T9 pipe is very parameter-sensitive and the process parameters have a very narrow range of allowance. Inadequate combination of process parameters causes the low quality of straightening, roll marks on the pipe's surface or crushing of the section. **Figure 1** shows these shape defects.

Many researchers have studied the fundamental mechanics of roller levelling processes. Talukder and Singh [1,2] studied the analytic dynamic load to eliminate the residual curvature that was unevenly distributed along the longitudinal direction of a pipe for various kinds of cross-roll levellers and revealed that the pitch is the most important factor to effect on the straightness of the levelled pipe. Li, Chen and Yang [3] suggested a mathematical model for the shape of rollers with the envelope theory and cutting path to process these rollers. They proved that this model satisfied the condition of the optimum line contact between the roller and the pipe. Wu *et al.* [4] made a mathematical model for the residual curvature in the pipe with two cross-rollers during levelling process and a quantitative model for the roundness of the levelled pipe supporting their model by experiments. Dvorkin and Medina [5] proposed a simple finite element model for analysis of the levelling process for seamless pipes, and showed that the cross-roll leveller could eliminate the curvature and improve the roundness of the pipe with finite element analysis results.

In order to obtain the accurate quantitative information, a systematic solution method is required to utilize DOE (design of experiment) and FEA (finite element analysis) as a very efficient tool to obtain the quantitative information on the roller levelling process. The Taguchi method can be one of the most efficient ways to evaluate the effect of the process parameters for the process design. It guarantees the robustness of the process despite existing noise factors such as the input noise and the noise caused by timeworn parts. In this paper, optimization of process parameters has been carried out for a multi-staggered-type 14-roller leveller. A finite element model of a multi-staggered 14-roller leveller was constructed for analysis whose results were verified by experiments. Process parameters that have the significant effect on the levelling process are identified through screening analysis with a fractional factorial design. The main analysis is carried out with the fractional model and the Taguchi method for evaluation of the effects of the process parameters. The optimum combination of process parameters is determined from the comprehensive result and its validity and reliability is confirmed by experiments.

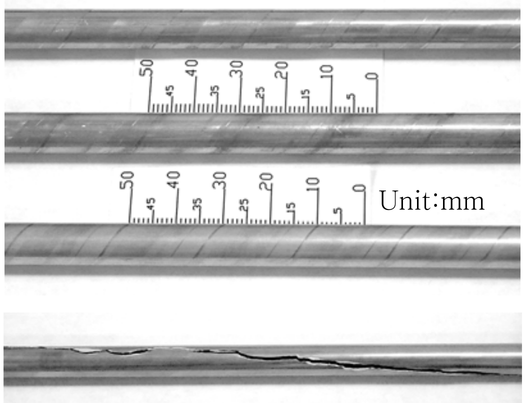

Figure 1: *Roll marks and section crushing of an Al7001T9 pipe.*

2 Fractional factorial analysis

A multi-staggered 14-roller leveller is modeled for finite element analysis of pipe straightening. Since finite element analysis with the full 14-roller leveller model requires excessive computation time, a fractional finite element model that consists of 7 rollers is constructed for the computational efficiency based on the knowledge of actual processes in the manufacturing industry. The seven rollers considered are the 2nd, the 3rd, the 4th, the 9th, the 10th, the 11th and the 12th. The paired set of the 1st–8th rollers is excluded since it plays a role of guide in inserting of pipes. The paired sets of the 6th–13th rollers and the 7th–14th rollers are also excluded from the analysis since they play a role of tracking and tensioning pipes. The scope of the analysis is confined to the functioning of the rest 7 rollers on the levelling process. **Figure 2** shows the full and fractional model of the roller leveller and **Figure 3** shows important parameters such as the slanted angle of rollers and the intermesh of rollers in the roller leveller.

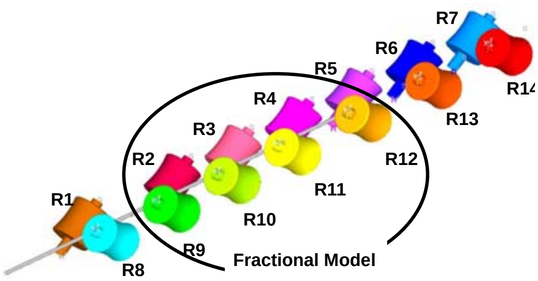

***Figure 2**: Full and fractional models of a multi-staggered 14-roller leveller.*

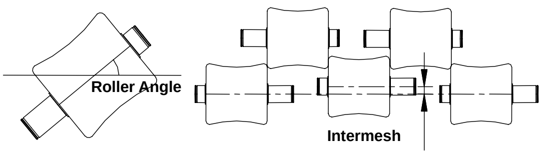

***Figure 3**: The slanted angle and the intermesh of roller.*

Rollers are modeled by the rigid body elements, and a pipe is modeled by the Belytschko-Wong-Chiang shell element with an elasto-plastic material of Al7001T9. Numerical integration is carried out at the three integration points along the thickness direction. The number of elements is 1200 and the number of nodes is 1224. Divisions along the circumferential direction and the longitudinal direction are 24 and 50 respectively. The stress-strain curve of Al7009T9 is shown with the mechanical properties in **Figure 4**. The feeding speed of a pipe is 1.64m/s in the factory and the rotational speed of each roller is calculated as 691rpm. The dynamic friction coefficient between rollers and a pipe is assumed to be 0.15. The finite element analysis is carried out with the commercial code DYNA3D [6].

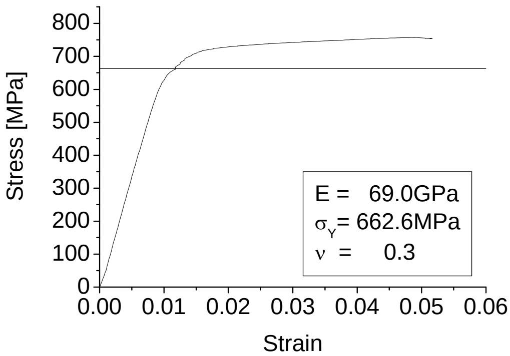

***Figure 4**: Stress-strain curve and some mechanical material properties of the Al7001T9.*

Significant process parameters in the levelling process are identified through screening analysis of a fractional factorial design. Analysis results with the fractional model show that the most important parameters are the intermesh of the 10th and the 11th loading rollers on the right row of the leveller and the slanted angle of the whole rollers as well as their allowable ranges. Results show that the intermesh of the 10th and the 11th rollers has to be larger than 3.5mm for the plastic deformation and the slanted angles of the whole rollers has to be larger than 35 degrees for smooth progression of pipes without jamming.

3 Optimization of process parameters

The roller levelling process of an Al7001T9 pipe is so sensitive to variation of the intermesh and the slanted angle of rollers that levels of the intermesh of the 10th and 11th rollers and slanted angles of the whole rollers should be assigned with narrow allowance as shown in **Table 1**. The optimization of process parameters has been carried out according to Taguchi's $L_9(3^4)$ orthogonal table as shown in **Table 2** since the analysis takes only the main effect of three design parameters into account. The levelling machine has noise factors in the real process owing to the deterioration of the equipment and the tolerance of parts. In the roller levelling process, significant noise factors are the initial residual curvature of the unstraightened pipe and the distribution of the plastic strain in the straightened pipe. These noise factors are shown in **Table 3**.

***Table 1**: Level of process parameters*

Factor \ Level	1	2	3
Intermesh of 10th Roller	3.5mm	4.0mm	4.5mm
Intermesh of 11th Roller	3.5mm	4.0mm	4.5mm
Slanted angle of whole rollers	35°	36°	37°

***Table 2**: $L_9(3^4)$ orthogonal array*

No. \ Factor	Intermesh of 10th roller	Intermesh of 11th roller	Roller angle	Error
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

***Table 3**: Noise factors and their level*

<table>
<tr><td>Initial curvature of pipes</td><td colspan="2">1 (Average; κ=0.02337/m)</td><td colspan="2">2 (Maximum; κ=0.04139/m)</td></tr>
<tr><td>Data acquisition point</td><td>1 (Front)</td><td colspan="2">2 (Mid)</td><td>3 (Rear)</td></tr>
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Finite element analysis has been carried out according to the levels of noise factors with two models that have the initial curvature of 0.02337/m and 0.04139/m. In order to eliminate the two initial residual curvatures, the longitudinal plastic strain needs to be 1.0635×10^{-4} and 1.88327×10^{-4} respectively. As the difference of the target value from the acquired value becomes smaller, the effect of the process parameter becomes greater. Consequently, the smaller-the-better type characteristic is appropriate to the loss function in this case.

4 Results and discussion

The average effect of factors has been depicted in **Figure 5** with respect to the level of factors. The figure explains that the effect of the variation of the intermesh of both 10th and 11th rollers is greater than that of the slanted angle of the whole rollers on the SN ratio. It is noted that the intermesh of the 10th roller should be as small as possible since the larger intermesh of the 10th roller results in the smaller SN ratio. The maximum intermesh of the 11th roller should be 4.0mm since the intermesh of 4.0mm or a larger value tends to decrease the SN ratio. Results of analysis of variance for the SN ratio are summarized in **Table 4**. While **Figure 5** shows that the intermesh of the 10th roller is 3.5mm and the slanted angle of the whole rollers is 35 degrees, **Table 4** shows that the most significant factor is the intermesh of the 11th roller and its optimum value is 4.0mm.

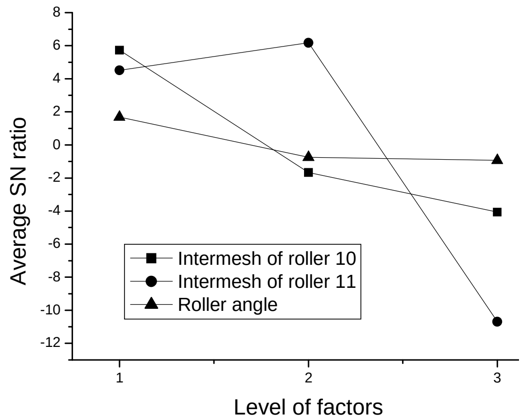

***Figure 5**: Average effect diagram of factors (smaller-the-better case)*

***Table 4**: Analysis of variance (ANOVA) for SN (Signal-to-Noise)*

Factor	Sum of Square	Degree of Freedom	Mean Square	F_0
Intermesh of 10th roller	156.4766	2	78.2383	1.0304
Intermesh of 11th roller	518.1007	2	259.0504	**3.4117**
Slanted angle of the whole rollers	12.7089	2	6.3544	0.0837
Error	151.8593	2	75.9296	
Total	839.1454	8		

***Table 5**: Experimental results and SN (Signal-to-noise) ratio*

No.	Intermesh of 10th roller	Intermesh of 11th roller	Slanted angle of rollers	Experiment	SN (Signal – to-Noise)
1	3.5mm	3.5mm	35°	Fair	-29.4473
2	3.5mm	4.0mm	36°	Fair	-27.9752
3	3.5mm	4.5mm	37°	Roll marks	-37.6452
4	4.0mm	3.5mm	36°	Roll marks	-29.6617
5	4.0mm	4.0mm	37°	Roll marks	-37.8057
6	4.0mm	4.5mm	35°	Fail	-49.8206
7	4.5mm	3.5mm	37°	Roll marks	-39.6156
8	4.5mm	4.0mm	35°	Fail	-27.9693
9	4.5mm	4.5mm	36°	Fail	-56.8642
Optimum value (smaller-the-better)	3.5mm	4.0mm	35°	Fair	**-26.6726**

In order to confirm the validity of optimization for process parameters of the roller leveller with the finite element analysis and the Taguchi method, experiments were carried out with the optimum condition of process parameters and the orthogonal array used in the finite element analysis as shown in **Table 5**. ‘Fair’ indicates that a pipe was levelled successfully but not perfectly, ‘Roll marks’ indicates that roll marks were induced on the pipe’s surface, and ‘Fail’ indicates that the levelling process was not completed because jamming impeded the progress of a pipe in the levelling process. The levelling process with the optimum condition was performed successfully, although the slight curvature remained in the pipe. Middle parts of **Table 5** show that the intermesh of the 10th roller of 4.0mm or a larger value causes bad effect on the levelling process because of jamming and roll marks. This result is in good agreement with the smaller-the-better type loss function explained with **Figure 5**. The optimum values for the intermesh and the slanted angle have been confirmed with the experimental results carried out according to the orthogonal array. They have been also proved to be the real optimum by showing the greatest value of the SN ratio. These results also suggest that combination of the finite element method and the Taguchi method puts confidence in the analysis and optimization of the levelling process.

5 Conclusion

This paper demonstrates optimization of process parameters for a multi-staggered-type 14-roller leveller with the finite element analysis and the Taguchi method. The optimum condition for the intermesh and the slanted angle was confirmed with the experiments of the orthogonal array. Significant process parameters were identified for the levelling process through screening analysis of a fractional factorial design. The main analysis has been carried out with the fractional model and the Taguchi method for evaluation of the effect of process parameters. The response variable was set to the plastic strain along the longitudinal axial direction of the pipe. Two noise factors were taken into account: the first was the initial residual curvature of a pipe; and the second was the variance of the plastic strain in the pipe. The optimum combination of process parameters was determined from numerical analysis results and verified by experiments. The two results showed excellent correspondence with each other, which also confirmed the validity and reliability of the present analysis.

6 References

[1] Das Talukder, N. K. and Singh, A. N.; Mechanics of bar straightening, Part 1: General analysis of straightening process, Trans. ASME, Vol. 113(1991), 224-227.
[2] Das Talukder, N. K. and Singh, A. N.; Mechanics of bar straightening, Part 2: Straightening in cross-roll straighteners, Trans. ASME, Vol. 113(1991), 228-232.
[3] Li, K. Y., Chen, C. K. and Yang, S. C.; Profile determination of a tube-straightening roller by envelope theory, J. Mater. Process Tech., Vol. 94(1999), 157-166.
[4] Wu, B. J., Chan, T. C., Lee, T. C. and Ao, L. W.; A study on the precision modeling of the bars produced in two cross-roll straightening, J. Mater. Process Tech., Vol. 99(2000), 202-206.
[5] Dvorkin, E. N. and Medina, F. M.; Finite element models for analyzing the straightening of steel seamless tubes, J. Eng. Ind., Vol. 111(1989), 351-355.
[6] Hallquist, J. O.; LS-DYNA User's Manual, (1999), Livermore Software Technology Corporation.