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EXAMINATION OF THE ACTUAL ROLL FORMING PROCESS USING FINITE ELEMENT ANALYSIS FOR IDENTIFICATION OF EDGE WAVES

Changwoo LEE[1] and Yonghui PARK[2*]

To widen the usage of the roll forming process, the shape of the pipe was compared by changing operating conditions with finite element analysis. Especially, the thickness of the skelp and the roll gap between upper and bottom rolls at Forming and Finpass stages were investigated to identify why the edge wave occurs and how it occurs when these two variables change without any change of a design variable in the field. Based on the results, this paper proposes the operating conditions and solutions that can be operated in the field to stop to produce defective pipes.

Keywords: roll forming, edge wave, roll design and gap, finite element analysis

1. Introduction

Roll forming technology aims to make a continuous steel pipe shape while passing a skelp between upper and lower rolls of various stages, and has advantages in terms of rapid productivity, so domestic steel pipe makers have used this technology (Figure 1). This forming technology has been able to produce various shapes of products such as under-rail slides, internal parts for automobile, and architectural and living products, so various industries have been trying to secure the technology. Especially, being possible to form high-strength skelp through roll forming, Computer Aided Engineering (CAE) approaches for minimizing the springback phenomenon have been performed.

In the domestic case, finite element analysis for simulating the elongation process of seamless pipe was used to predict the formability change due to roll rotation speed and torsion angle [1]. Analysis of variable sectional roll forming process, including pre-heating process for high strength pipe [2-3], analysis of the roll forming process of high strength, long rail for vans seat [4], and optimization of 18-stage roll forming process for under rail slide were also conducted [5]. In this way, makers of automotive and machinery parts have tried to secure product formability and to minimize the springback effect through CAE technology. On the other hand, the steel pipe industry has secured quality assurance and test evaluation technology in priority for satisfying domestic and export standard. In

[1] POSTECH & Pohang Institute of Metal Industry Advancement, Korea, e-mail: cw82.lee@pomia.or.kr
[2] Yuhan University, South Korea, e-mail: yhpark@yuhan.ac.kr

addition, since steel pipes that meet overseas standards have been produced with the initially invested roll forming process facilities, there was no need to increase or replace the facilities. In this awareness, pipe makers have chosen to produce new product lines such as high-strength thin-walled products by changing operating conditions including roll gaps based on accumulated experience without any models. However, since the roll forming has lots of variables that affect the formability seriously compared to other technology, the variables should be verified through CAE instead of their own experience.

In this paper, we defined finite element analysis that simulates the roll forming process that produces steel pipe with a thickness of about 2 mm or less. To verify the formability of the pipe and to validate the model, the girth variation of the skelp was calculated by using the model and was compared to the girth variation that is measured. Especially, we set the roll gap between the upper and bottom rolls and the thickness of the skelp, which are the main process variables, as variable numbers, and identified the trends of edge wave phenomena and their correlation. Then, in the two-dimensional finite element analysis model, the contact surface distribution among the upper and bottom rolls and skelp was analyzed to identify the cause of the edge wave [6]. Based on these results, we suggest the operating conditions and solutions that can be operated in the field to stop to produce defective pipes.

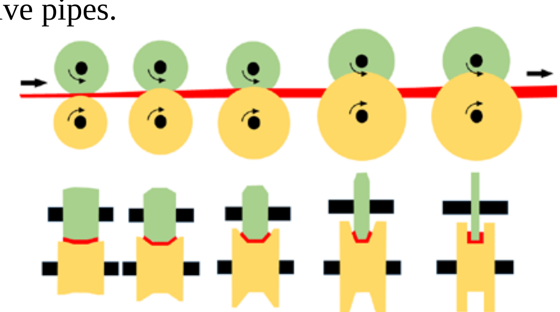


Fig. 1. Roll forming

2. Overview of the roll forming process

In the entire roll forming process, the skelp is uncoiled from the coil, and is transferred into the inlet between the upper and bottom rolls at the Forming 1 stage. The skelp is bent as the shape of pipe by passing through the Forming and Finpass stages sequentially. After that, the edge parts are joined by electric resistance welding, the material is secured by local heat treatment, and the steel pipe product is obtained through final cutting. This study covers the forming process before the electric resistance welding.

The roll forming process consists of four stages of the Forming and three stages of the Finpass, with two side rolls positioned between the stages to match the center of the skelp (Figure 2). Each Forming and Finpass stage consists of upper and bottom rolls, and the operation is performed by adjusting the roll gap between the upper and bottom rolls and the roll rotation speed. In the case of the side roll, including the FOI and FPI, the idle state is in which the rotation of the FOI and FPI occurs due to the frictional force generated by the contact with the skelp.

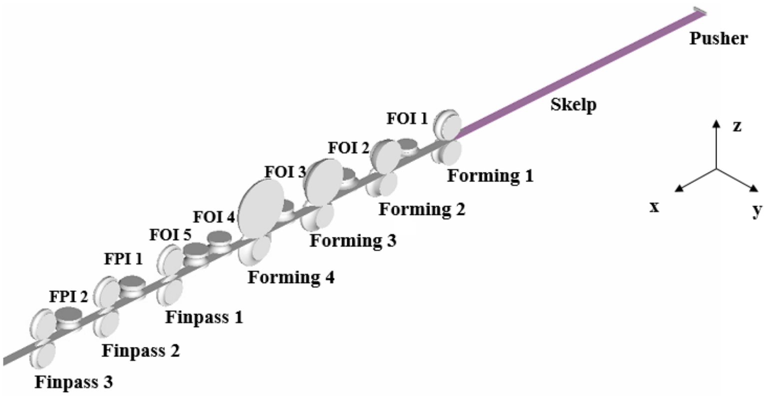


Fig. 2. Three-dimensional finite element model for the roll forming process

2.1. Overview of the three-dimensional finite element model

A three-dimensional y-direction symmetric finite element model with ABAQUS was developed by using field roll drawings and operating conditions to simulate Elasto-plastic deformations of the skelp (Fig. 2). All rolls have rigid body motions and the operating conditions in the field, including the roll rotation speed, were applied. From Forming 1 to Finpass 3, each roll rotates at ω_{Form1}, ω_{Form2}, ω_{Form3}, ω_{Form4}, ω_{Fin1}, ω_{Fin2} and ω_{Fin3} respectively. Of course, the upper and bottom roll rotates different direction such as clockwise and counter-clockwise direction about the global coordinates. FOI 1 ~ 5 rolls rotate by contact friction with the skelp. In other words, they are idle.

To simulate Elasto-plastic deformations of the skelp, the skelp has hexahedron element, and has AISI-1137 material properties that is close to API-X52 material property. This material has yield strength about 344 MPa and tensile strength about 584 MPa. About mesh, the hexahedron elements were divided into a number of elements such that the element length in the width direction (y direction) and the element length in the longitudinal direction (x direction) were maintained at a 1: 4 ratio based on the element length in the direction of the thickness of the skelp (z direction). Even though the pusher is not present in the actual process, but it was defined to stably feed the skelp to the Forming 1 rolls. Since the linear velocity of the pusher is lower than the linear velocity of the surface of each roll, the pusher is no longer in contact with the skelp when the forcing is applied on the skelp between the upper and bottom rolls. This time-dependent problem is solved by dynamic explicit solver and is planned to stop when the end of the skelp pass through Finpass 3 stage. The roll forming process did not consider heat transfer in the cold forming process. In this model, it is possible to analyze according to the requirements of operators such as parametric analysis on the steel pipe formability, and the adjustable variables are shown in Table 1.

Table 1

Design variable and operating conditions

Part	Design variable	Part	Operating condition
Skelp	Material property	Skelp	Initial linear velocity
	Dimension (Length, width, thickness)		Initial position (y and z directions)
Roll	Roll design	Roll	Rotation speed
			Position (The center of rotation (x, y, z))
		Contact	Friction coefficient

2.2 Model validation

To examine the feasibility of the model, the variation of girth length in the skelp was selected as the comparative physical quantity. The variation of girth length is the main factor determining the pipe formability in the field, and controlling it by using Forming factor, F_f (1).

$$F_f = \frac{G_f - G_i}{t} \tag{1}$$

F_f = Forming factor
G_f = girth length of the skelp at the end of the Forming 4 stage [mm]
G_i = initial girth length of the skelp [mm]
t = thickness of the skelp [mm]

For example, the target G_f is set to satisfy the optimum value of F_f, and the roll gaps at the Forming 1 to 4 stages are adjusted so that the desired G_f is obtained at the end of the Forming 4 stage.

To verify whether the model correctly simulates the roll forming process occurring in the actual process, a comparison was made to the experimentally measured value of the outer girth length of the skelp at the same position after each stage (Eq. 2, Fig. 3). The girth length was measured when the skelp is sandwiched all rolls and all rolls are stopped. The reason of selecting the girth length to validate the model, is to check whether the model is good to show formability or not compared to the real. This problem has high non-linear behavior such as isotropic and kinematic hardening, so it is impossible to develop accurate model that has no difference. However, we can expect the trend by changing a parameter with the proper model validated by checking formability such as the girth length. Two variations of the girth length are similar with *ΔG* difference within 1%, taking into account all the upper rolls in the absence of contact with the skelp and the error of the measurer and the equipment in the actual measurement.

$$\Delta G = \frac{G - G_i}{G_i} \times 100 \qquad (2)$$

ΔG = variation rate of the girth length [%]
G = measured or calculated girth length [mm]
G_i = initial girth length [mm]

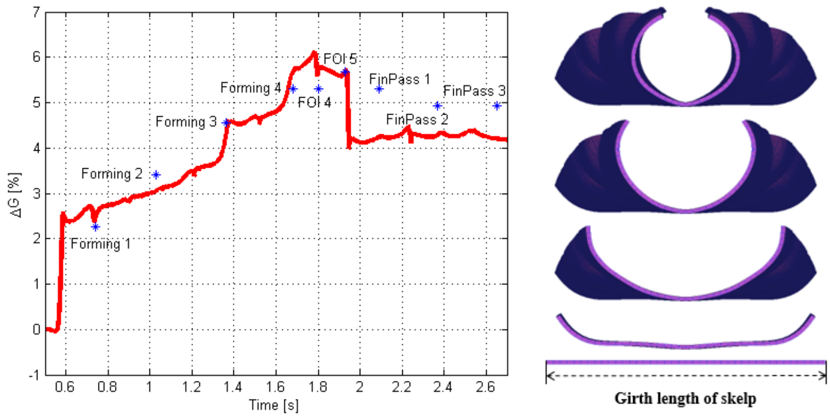


Fig. 3. The variation of girth length: red line (model), blue point (measured)

3. Simulation condition

3.1. Problem definition

Edge wave is a typical phenomenon in which a wave-like plastic deformation occurs at the edge of the skelp, and domestic steel pipe makers have tried to solve this problem to produce high strength thin pipes [6]. After the edge stretch phenomenon was firstly studied by investigating the relationship between the edge stretch, pipe diameter and roll design [7], several methods had been suggested to reduce the edge wave [8-10]. Especially, until recently double bending method at the initial stage of the forming process [11], control of the inlet angle of the center line of the skelp, and slight tension on the skelp at the final pass have been chosen to prevent edge wave formation [12]. In addition, numerical simulation that see the edge wave according to the longitudinal bending of the formed profile [13], experiment by varying the thickness of the skelp to check the trend of the edge wave [14-15], and numerical model for predicting edge instabilities [16] have been conducted consistently. Although previous studies have suggested the cause and the solution of this phenomenon, the solution is not a perfect solution in many roll forming processes because the solution is confined to specific design parameters and conditions and it is hard to substitute exact solution to the field line. Therefore, to investigate the problem of edge wave occurring in the actual process, we analyzed the cause of edge wave and discussed the solution through the sensitivity analysis according to the parameters of the model. At this time, the roll gap between the upper and bottom rolls of the respective Forming and Finpass stages were changed in the same value as that of the thickness of the skelp. Through the analysis, the plastic strains of the elements and nodes at the same edge of the skelp were compared.

3.2. Edge wave due to the roll gap and thickness of the skelp

To solve the on-the-spot worries about whether the correct process can be performed when changing the thickness of skelp and roll gaps between upper and bottom rolls without any change in roll design, we simulated seven cases by applying different thickness of the skelp and roll gap, t_i, as t_1=t_m, t_2=t_m-0.2, t_3=t_m-0.5, t_4=t_m-0.8, t_5=t_m-1, t_6=t_m-1.2, t_7=t_m-1.4, based on the thickness of the skelp and roll gap t_m [mm] used in the actual steel pipe production. The variables except for the two variables were fixed at the conditions used in the field. Since the edge wave were generated while the thin steel pipe is manufactured in the same way in the field, it is necessary to simulate the same process conditions and to present the solution.

3.3. Contact surface distribution among the upper and bottom rolls, and skelp with varying thickness of the skelp

By using ABAQUS, a two-dimensional finite element analysis was performed to check the contact surface distribution between the upper and bottom rolls, and skelp (Fig. 4). Although the problem is difficult to simplify the roll forming process to two-dimensional plane strain and plane stress problem, plane strain problem is assumed to see the contact surface distribution due to the fact that the roll gap and thickness of the skelp are the same so that many deformations do not occur in the longitudinal direction as in the rolling process. Although this assumption is difficult to give an accurate calculation of the stress distribution in the skelp, checking the contact surface between the roll and skelp has no problem. Since the two-dimensional problem is composed of a small amount of computation compared to the three-dimensional problem, a fine element was defined in the skelp, and the roll gap and thickness of skelp were smaller than or larger than t_m as in the previous section to prove the fact that the change of t_i is not right without the change of roll shape in the real process. About simulation condition, all parts contact each other as the upper roll goes down. The bottom roll is fixed and the upper roll stop to move when the distance between the upper roll and bottom roll reaches t_i. This problem is not time dependent, so static analysis with non-linear solver was used.

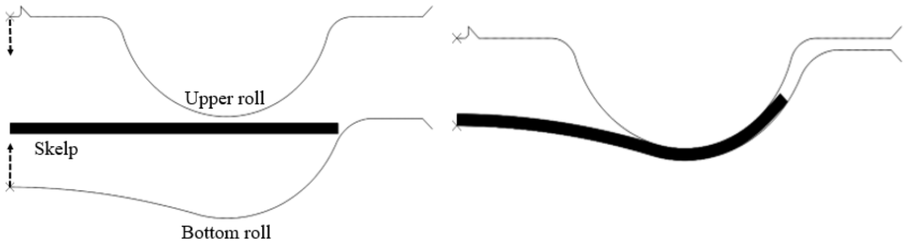


Fig. 4. Two-dimensional plane strain problem between the upper and bottom rolls and skelp

4. Results and discussion

4.1. Shape of the skelp at each stage

Figure 5 shows the shape of the skelp immediately after each roll forming stage. After W-bending in the Forming 1 stage, we can see that bending is done to the final target radius *R* of the steel pipe through the Forming 2 ~ Finpass 3 stages. In this case, in the longitudinal plastic strain $\varepsilon_{p,x}$ distribution of the skelp at each step, it can be seen that the sections that have the greatest influence on the skeletal edge are the Forming 1 and Finpass 1 ~ 3 stages (Fi. 6). Especially, a rapid compressive plastic deformation occurs due to the compressive force in the vicinity of the edge after the Forming 1 stage, and a relatively high plastic deformation occurs on the outer surface of the skelp after the Finpass 1 ~ 3 stages. Therefore, we need to focus on the relationship between t_i and edge wave on the Forming 1 and Finpass 1 ~ 3 stages.

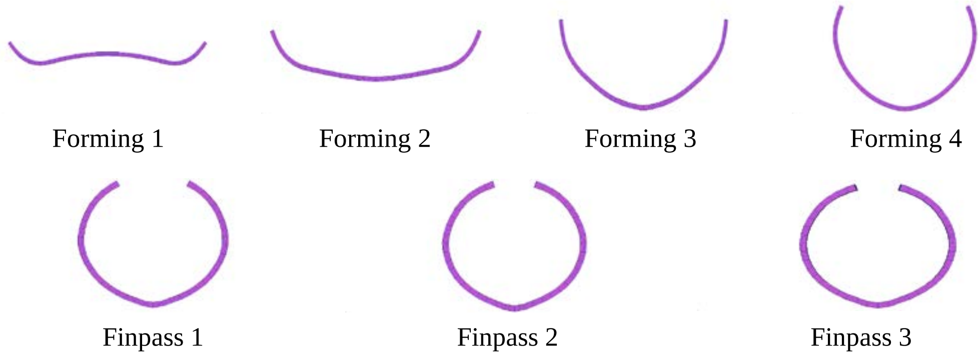


Fig. 5. Shape of the skelp after each roll forming stage

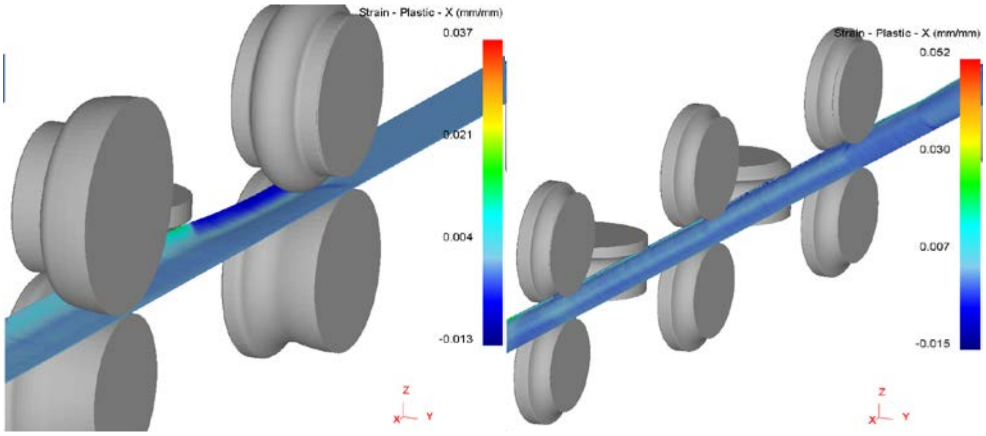


Fig. 6. $\varepsilon_{p,x}$ distribution near the edge of the skelp;(L) after the Forming 1 stage; (R) after the Finpass 1 ~ 3 stages

4.2. Relationship between the edge wave and t_i

In the results of the analysis, even if the thickness of the skelp and roll gap between the upper and bottom rolls were changed the same, as t_i became thin, edge wave occurred repeatedly with tensile and compressive plastic deformation along the longitudinal direction of the skelp (Fig. 7). Looking at the distortion of the mesh, the edges of the lower surface of the skelp touching the bottom roll of the Forming 1 stage were heavily distorted. Especially, from the thickness below t_4, the distortion became heavy and the solution was not converged. On the other hand, in the Finpass stages, the edge deformation is relatively large due to the contact between the upper roll and edge of the skelp due to the finishing work of bending the skelp into a steel pipe shape, but the curvature of the skelp is close to the final radius R of the steel pipe, so complicated shape change, including the edge wave, did not occur.

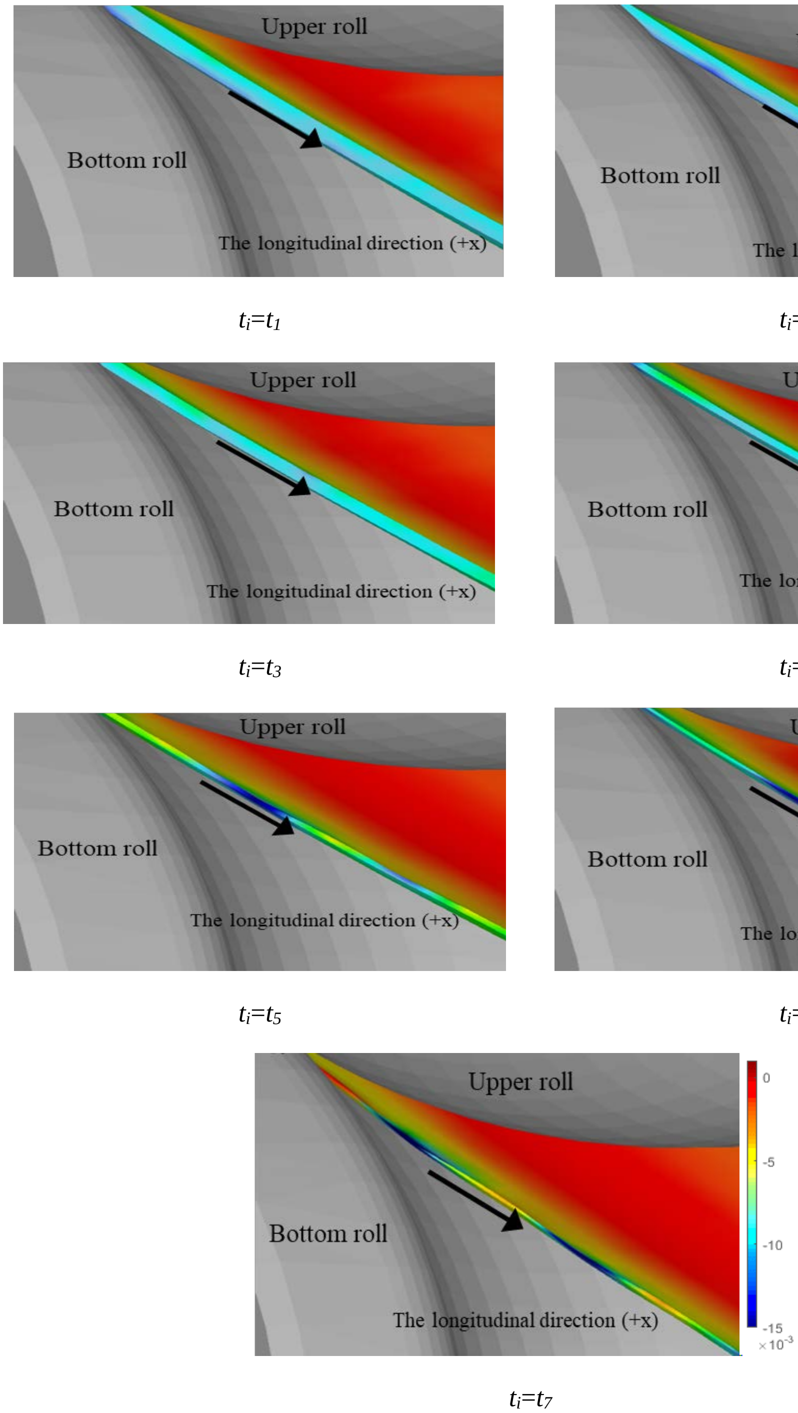
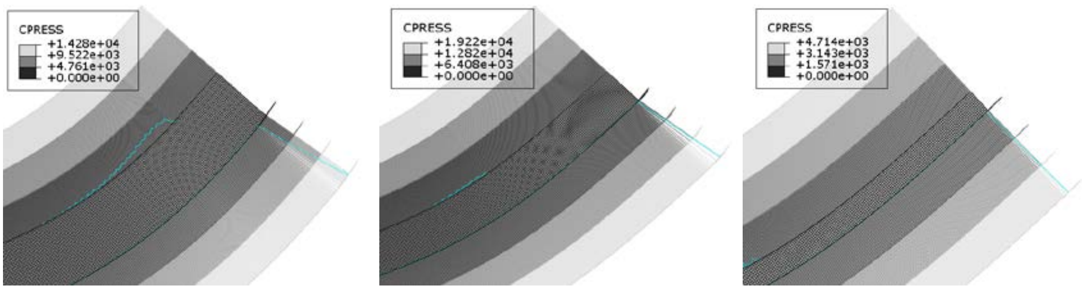


Fig. 7. $\varepsilon_{p,x}$ distribution at the edge of the skelp at the Forming 1 stage

4.3. Decrease of the contact surface distribution due to reduction of t_i

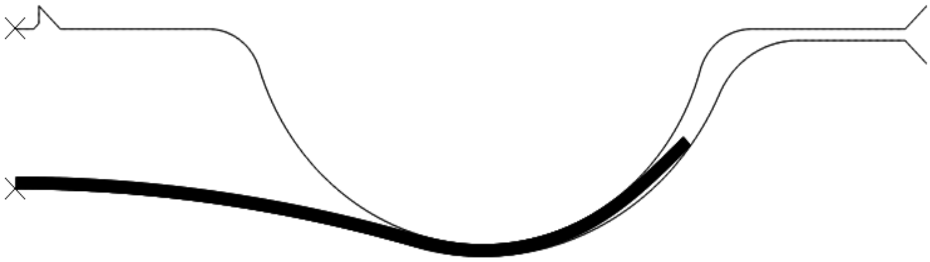
By applying different thickness of the skelp and roll gap, t_i, to the two-dimensional model, the contact surface area between the upper roll and skelp decreased as t_i decreased (Fig. 8). This means that the contact is concentrated only in a specific area and is not uniformly distributed. In the analysis in which t_i is larger than the reference t_m, the right end of the contact surface between the upper roll and skelp is near that of the contact surface between the bottom roll and skelp, but the right end of the contact surface between the upper roll and skelp is going further away from that of the contact surface between the bottom roll and skelp as t_i decreases. As a result, the probability of occurrence of the edge wave due to the difference in relative speed is increased. Particularly, as t_i decreases without changing the roll design, the difference in distance between the two points increases, and the probability of buckling further increases.

There are various methods to prevent edge wave when the t_i is small. A method of the process of bending the skelp in V shape before the Forming 1 stage, method of modifying the shape of the upper roll to touch the edge of the skelp, and method of adjusting operating conditions such as reducing the roll gap that is lower than the thickness of skelp or adjusting the roll rotation speed, but the last method can generate the center wave by raising the center of the skelp from the bottom roll, is necessary to review and apply them carefully (Fig. 9).

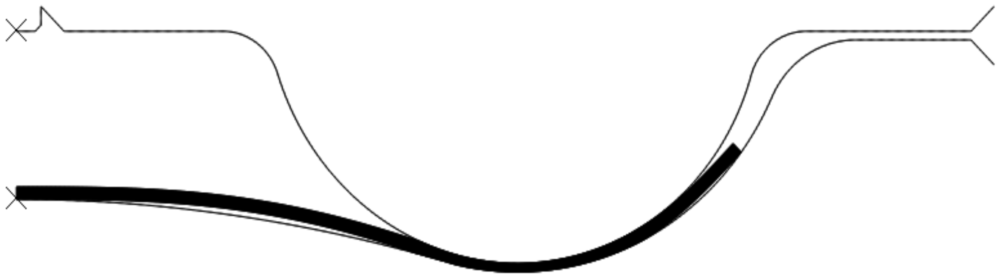


$t_i = t_m+1$ $t_i = t_m$ $t_i = t_m-1$

Fig. 8. Contact surface distribution and contact pressure according to the thickness of skelp and the roll gap, t_i; mint line



The thickness of the skelp = The roll gap = t_m-0.1



The thickness of the skelp = t_m-0.1 & The roll gap = t_m-0.3

Fig. 9. Deformation of the skelp according to the thickness of the skelp and roll gap

5. Conclusion

In this study, the finite element analysis models of the pre-installed roll forming process were established and the application of the process according to operating conditions was examined. We investigated the suitability of the model by examining the variation of the girth length of the skelp in each roll forming stage and verified plastic strain on the skelp to find out the relationship between the edge wave and operating conditions. In particular, seven analyzes were conducted to compare the effect of changing the thickness of skelp and roll gap on the occurrence of edge wave. Compared with the results of the two-dimensional analysis, buckling, including the edge wave, occurs due to the reduction of the contact surface between the upper roll and skelp at the Forming 1 stage, when the thickness and roll gap is lower than the standard value. Although the results focus on the edge wave, these models have the advantage of confirming operating conditions that cause other defects such as center wave. In the future, it is planned to confirm whether it is possible to produce a small-diameter steel pipe with a small thickness when simply changing the operating conditions or changing the shape of the upper roll of the Forming 1 stage without any other changes such as the roll design.

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