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ORIGINAL ARTICLE

Investigation of the cause of the chatter and physical behavior of a work roll in compact endless rolling

Dong Kyu Lee[1] · **Jiwoo Nam**[1] · **Jin Su Kang**[1] · **Jea-Sook Chung**[2] · **Seong Wook Cho**[1]

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Abstract Mechanical devices that contain many rotating elements such as rolling mills inevitably generate vibrations. Vibrations not only cause unnecessary loads but also affect the quality of the manufactured product. Therefore, it is important to identify the causes of vibration in such mechanical devices and control them appropriately. In this study, the various causes of vibration in a rolling process were investigated, and the vibration types present in a compact endless-rolling mill (CEM) process were analyzed and compared. Three typical causes of vibration were analyzed. Based on these results, the cause of the vibrations that occur during changes in the processing conditions in a CEM can be inferred. More specifically, numerical analysis was conducted to study the physical behavior of work rolls (WRs) according to changes in the rolling process conditions. Using these analysis results, a mechanism to produce vibrations similar to those occurring in a CEM was proposed. The results of tracking the center position of a work roll showed that the direct effects of contact pressure on vibration were minimal, and changes in the lubrication type for the physical interaction between a WR and the contact strip were identified as a cause of vibration.

Keywords Chatter · Stribeck curve · Rolling · Contact analysis

1 Introduction

In recent years, the demands on strips have increased in various industrial fields. As a result, the steel industry has focused on improving the productivity of strips. The rolling processes used for manufacturing strips can be divided into two types: cold rolling and hot rolling. In the hot rolling process, an intermediate product (called a slab) is manufactured before a strip is manufactured through the cold rolling process. In a general rolling process, product defects are likely to occur at the top and tail of a slab; it is necessary to raise the temperature of the slab, which is a product of hot rolling, to an appropriate temperature for cold rolling. To overcome the above-mentioned inconvenience and to increase productivity, strips have started to be manufactured using the compact endless-rolling mill (CEM) process in recent years.

The CEM process utilizes a rolling technology that continuously produces strips without any idle time; a coil box (instead of a slab) is produced through hot rolling as an intermediate product. Strips are then immediately produced through a cold rolling process. This process joins the initial and trailing bars to the coil box, which has been manufactured through hot rolling, to remove possible product defects at the top and tail ends and reduce the required energy by removing the slab preheating process. This explains why the CEM process has superior productivity and cost effectiveness compared to general rolling processes.

A rolling mill that manufactures strips is a complex mechanical device with many rotating elements, including a back-up roll, work roll, rolling element, and bearings. In general, these rotating elements inevitably generate vibration as they rotate; such vibration in mechanical devices, e.g., rolling mills, is called chatter. The causes of chatter can be divided into two main categories: (1) internal causes resulting from defects and damage to the rotating elements and (2) external

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✉ Seong Wook Cho
scho@cau.ac.kr

[1] School of Mechanical Engineering, Chung-Ang University, Heukseok-Dong, Dongjak-Gu, Seoul 156-756, South Korea

[2] POSCO Endless Rolling Team, POSCO Gwangyang Works, 700, Gumho-dong, Gwangyang 545-711, South Korea

causes due to additional rolling process elements such as lubricants and rolling loads [1, 2].

Chatter in the rolling process not only induces product damage but also accelerates wear on the work rolls and causes damage to the rolling mill. It has been reported that larger amplitude vibrations accelerate this wear more quickly. In the CEM process, a new type of vibration can occur (one that has not been experienced before) whose amplitude increases over time to interrupt operation of the CEM process. To determine the cause of this problem and provide a solution, this study analyzed various vibration generation theories for cold and hot rolling as well as for CEM processes. We also proposed a method of vibration flow by comparing the analysis results with the vibration characteristics in the current CEM process.

To achieve these objectives, the causes of regenerative effects, the Stribeck curve, and the type of lubrication were studied. Parametric numerical analysis was conducted using a finite element model (FEM) in order to understand the physical behavior and possible causes of vibration generation in work rolls. The results verified that the physical behavior (i.e., contact pressure and frictional stress) relative to the changes in the rolling process parameters did not directly affect the vibration characteristics and functions that include the physical behaviors of the COF of the contact area between the work roll and the strip should be applied to analyze changes in the vibration characteristics.

2 Analysis of the cause of chatter

To manufacture products that are thinner than previous products, the current process was still used, but the reduction ratio was changed during the manufacturing process. As a result, vibrations were generated with gradually increasing amplitudes over time, and the rolling process was terminated without reaching the preferred number of strip coils per charge. To solve this problem, the causes of these such vibrations were studied.

2.1 Regenerative effect

The regenerative effect is a theory explaining vibration generation in cutting processes. A cutting process, in which the cutting material is rotated, inevitably generates vibration in the initial stage. This initial vibration creates irregular work piece surfaces, which then cause vibrations in the cutting tools. Vibrations in the cutting tools, which are caused by the initial vibration, repeat the irregular surface generation found in the work pieces during the cutting process. The irregular surfaces of these work pieces, which are caused by the initial vibration in the cutting tools, generate continuous vibrations by interacting with each other. Vibration caused by the regenerative effect may occur in greater or lesser amounts depending on the cutting process conditions. In particular, as the rotation speed, cutting width, and feed rate of the work pieces increase, the vibration also increases [3]. Similarly, rolling processes can also experience continuous vibration during the subsequent rolling process, primarily due to the continued effects caused by the initial vibration [4].

Figure 1 explains the relationship between a continuous rolling mill and a strip. Owing to the initial vibration in the work roll, changes in the gap size occur between the upper and lower parts of the work roll in the rolling mill. Here, assuming that the mass flow of a strip entering the rolling mill is constant, the speed of the outgoing strip changes due to changes in the work roll gap. This characteristic will cause the speed and thickness of the second strip entering the rolling mill to be irregular, thereby generating a change in the gap between the upper and lower parts of the second rolling mill work roll. The vibration of irregular rolling mills causes the speeds of both incoming and outgoing strips to be irregular. Continuous rolling mills exchange vibration with one another using these strips. Owing to the different rotational speeds in a continuous rolling mill, tension is generated in the strips. This tension induces vibrations in the transverse direction of the rolling mill, thereby creating a coordinated vibration phenomenon in the overall system [5].

As the vibration persists via the continuous interaction between the rolling mills, this type of vibration can gradually increase if it falls into a specific loop. In previous studies, the tension due to the differences in speed between continuous rolling mill elements was determined to be a factor that influences vibration development. The system was found to become unstable as the vibration amplitude increased and the vibration fell into a positive feedback loop when the tension in the strips reached a certain condition [6, 7].

2.2 Stribeck curve gradient

The coefficient of friction (COF) is a factor determined by the characteristics of the interface between two surfaces. In particular, the COF is determined by the type of lubrication, the lubrication characteristics, and the friction in the working environment (which is controlled by the lubrication). The COF influences various factors, such as the rolling load, friction between the strip and work roll, and wear on the work roll. Therefore, because the COF is a very important factor that can change according to the process environment, it is very important for predicting and controlling the COF.

Figure 2 explains the Stribeck curve. This curve depicts the relationship of the COF with the viscosity, speed, and unit load in processes controlled by the lubricants (e.g., rolling processes). Lubrication can be divided into three types: (a) boundary lubrication, (b) mixed-film lubrication, and (c) hydrodynamic lubrication. The lubrication type is determined by

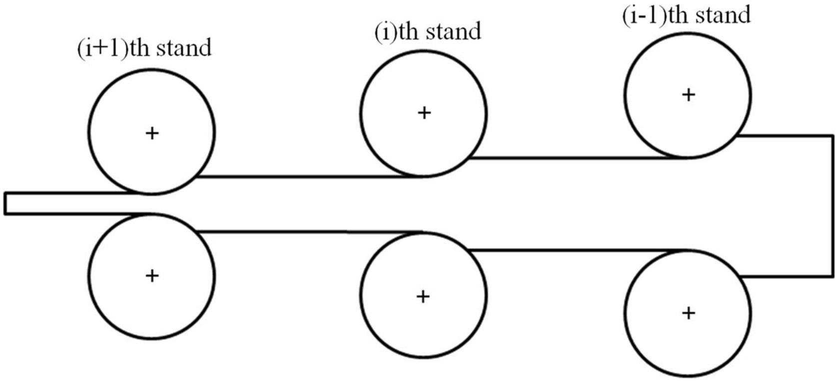

Fig. 1 Relationship between mill stands

the lubrication conditions at the interface. The COF behavior changes as the viscosity, speed, and unit load are changed according to the lubrication conditions.

In a rolling process, the lubrication type is determined by the process environment and strip conditions. In particular, a rolling processing system is stable under hydrodynamic lubrication; however, depending on the processing conditions, chatter may increase if the gap between two interfacing surfaces becomes a mixed-film type of lubrication. This characteristic can be determined by the slope of the Stribeck curve. Mixed-film lubrication and boundary lubrication both have negative slopes, while hydrodynamic lubrication has a positive slope. Thus, the slope of the Stribeck curve is one factor that determines whether or not chatter develops [8].

2.3 Lubrication

The lubrication conditions in the strip and work roll are highly important to rolling processes. The lubricant increases the replacement period of a work roll by reducing the wear, while also protecting the work roll from constant high temperature and high pressure. Whether chatter occurs can also be determined by the lubricant type and conditions. Often, an initial lubricant has small emulsion particles; therefore, it can be easily spread over the interfacing surfaces. However, lubricant emulsion particles inside a lubricant tank can aggregate, creating unstable lubrication conditions that generate vibration [9, 10]. Friction at the interface between a strip and work roll depends not only on the lubricant itself but also on external factors. Because worn-out particles caused by work roll wear are present at the interfaces during the rolling process, the lubricant contributes to particle lubrication as opposed to hydrodynamic lubrication [11]. Vibration occurs due to the irregular COF caused by particle lubrication. To suppress the vibration generated by the lubricant, the chemical composition and type of lubricant may need to be changed [12].

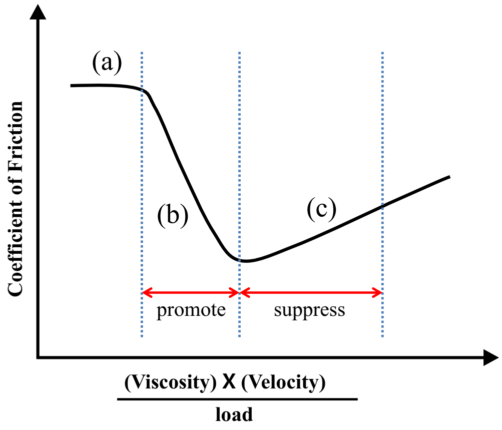

Fig. 2 Shift of the operating point on the Stribeck curve

In addition, there are many internal and external causes of vibration during rolling processes. The above three factors generate a vibration where the amplitude grows over time, similar to what happens during strip manufacturing processes.

3 Numerical simulation

3.1 Numerical modeling

In manufacturing strips thinner than those produced by existing processes, either the reduction ratio must be increased or the initial strip thickness must be reduced. The proposed process increases the reduction ratio of the rolling mill to achieve this.

Table 1 describes the rolling process conditions according to the presence of chatter. The process conditions are changed from those in Case 1 to those in Case 2. Hence, chatter appeared in areas where the vibration size gradually increased over time. A 2D numerical analysis was conducted for the 52, 57, and 62% reduction ratios to analyze this phenomenon and determine the changes in the rolling loads corresponding to the increasing reduction ratio. Various rolling simulations aimed at understanding strip displacement and residual stress were previously conducted. Therefore, for a more efficient calculation, this study performed an analysis assuming that the work roll was a rigid body. This assumption was made because the work roll strain was minimal compared to the changes in the strips. We also assumed that the work roll

Table 1 Information on the rolling parameters and the chatter

Information	Case 1	Case 2
BR diameter	1450 mm	
WR diameter	650 mm	
Strip yield stress	105 MPa	
Thickness	6.48 mm	
Reduction	52%	57%
Chatter	X	O

was an elastomer in order to determine the effects of reducing the stress distribution on the work roll surfaces. Figure 3 shows a symmetrical 2D model used for efficient calculation. The augmented Lagrangian contact condition was applied to the contact areas of the WR-strip and the WR-BR. Three element meshes were then created along the thickness direction of the strip. Similar to an actual rolling process, the WR was rotated, and the rolling process was performed through WR and BR contact by applying a rotation speed of 171 rpm to the BR. A 2D-plane element with eight nodes was used to increase the solution accuracy. In this analysis, 13,373 elements and 12,495 nodes were used. The rolling process was simulated by rotating a back-up roll.

3.2 Simulation of the previous rolling process

Figure 4 shows the distributions of the contact pressure and shear stress on the work roll surface. The highest contact pressure was detected at the center of the surface, while the size and direction of the shear stress varied around the neutral point.

Figure 5 shows the distributions of the contact pressure and shear stress on the work roll surface. For the contact pressure, a larger reduction ratio tended to produce a larger contact pressure. For the shear stress, no significant difference was observed between reductions of 52 and 57%, but the 62% reduction showed a significant increase in shear stress.

The numerical analysis results demonstrate that the contact pressure (per unit length) increased as the reduction ratio increased. Considering that the occurrence of chatter was determined by an increase in the load per unit length, the probability of chatter occurrence can be inferred from the Stribeck curve. By examining the above results (based on the Stribeck curve theory), it can be concluded that the interface conditions changed from (c) to (b) due to a considerable increase in the contact pressure, as shown in Fig. 2. In other words, it can be inferred that the initial chatter occurred when the lubrication type at the interface between the strip and work roll changed from hydrodynamic lubrication to boundary lubrication. The above results are also observed in general rolling processes, but the vibration occurring during the idle rolling time between slabs is removed in these general processes. Alternatively, in the CEM process (where rolling proceeds without idle time), the vibration amplitude increases continuously because the vibration develops continuously.

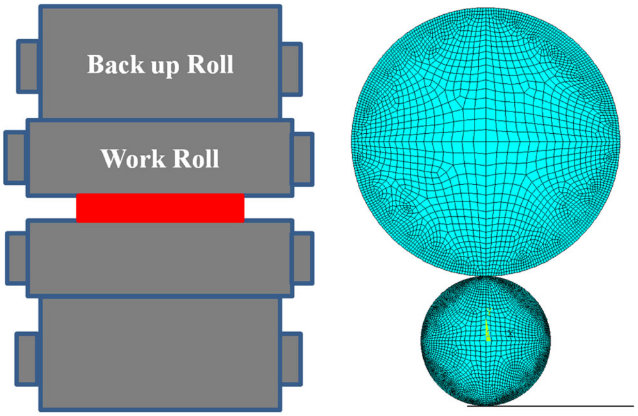

Fig. 3 Numerical model of the WR, BR, and strip

3.3 Parametric study

Based on a numerical analysis of previous rolling processes, the tendency of the rolling load to increase as the reduction ratio increases during strip manufacturing was found to cause the initial chatter (based on Stribeck curve theory). Thus, if we can identify a trend in the rolling load distribution based on the rolling process parameters, we may be able to suppress the chatter by reducing the rolling load through changes in the rolling process parameters. A numerical analysis was conducted to analyze the physical behavior according to the changes in the rolling process parameters prior to determining the vibration characteristics. This was achieved by examining the surface stress distribution on the work roll through numerical analysis of the changeable parameters (i.e., strip thickness, work roll radius, and strip yield stress). Table 2 shows the parameter information used in the numerical analysis.

Figure 6 illustrates the variations in contact pressure and shear stress. The contact pressure decreased as the diameter increased because of the larger distribution of the rolling force that resulted from the increased contact area. However, the effect of the diameter on the shear stress was minimal. The contact pressure increased as the initial strip thickness increased because of the increased reduction ratio needed to achieve the target thickness. Meanwhile, the contact pressure increased as the yield stress increased, owing to the increased load size, which initiated a plastic deformation. Alternatively, the shear stress generated by the wear of the work roll varied significantly as a function of the reduction ratio. However, the other parameters with similar effects did not significantly influence the shear stress.

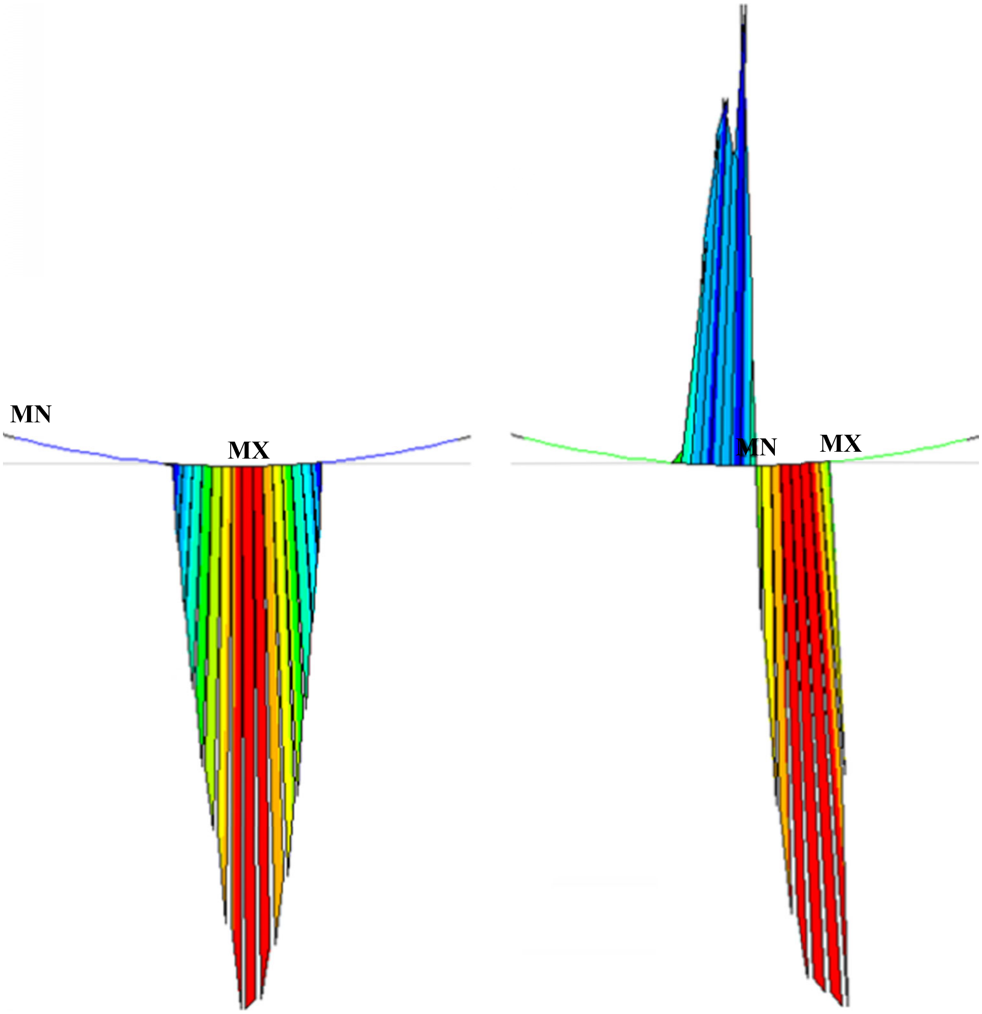

Fig. 4 Contact pressure and shear stress in the contact area

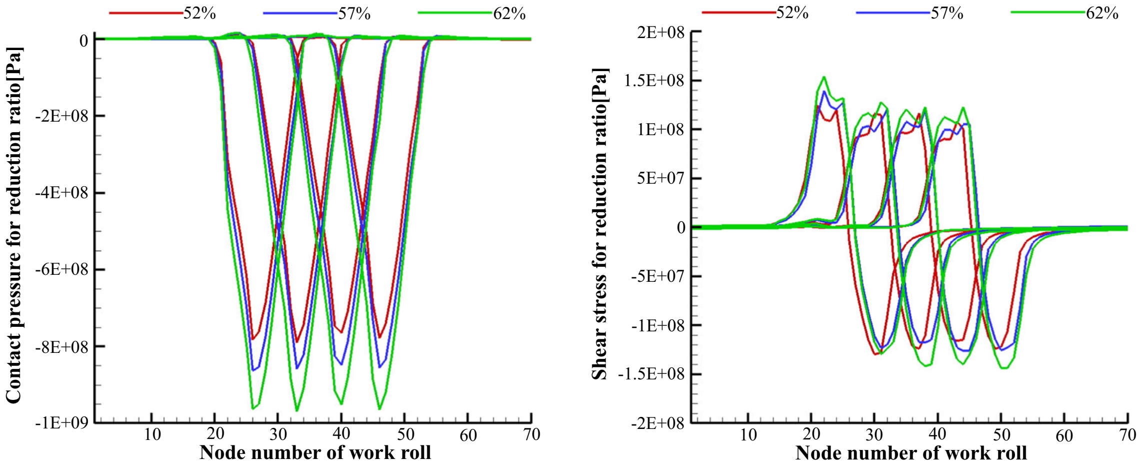

Fig. 5 Contact pressure and shear stress as a function of the reduction ratio

Table. 2 Information on the parameters used for numerical analysis

Parameter	1 level	2 level	3 level
Yield stress (MPa)	80	105	130
Diameter (WR) (mm)	600	650	700
Thickness (mm)	6.48	7.48	8.48

3.4 Tracing the center position of the work roll

The center node position of the work roll was traced according to various parameters to determine the effects of the work roll on the vibration and stress distribution.

Figure 7 presents the center node position of the work roll with respect to each parameter. The physical behavior at

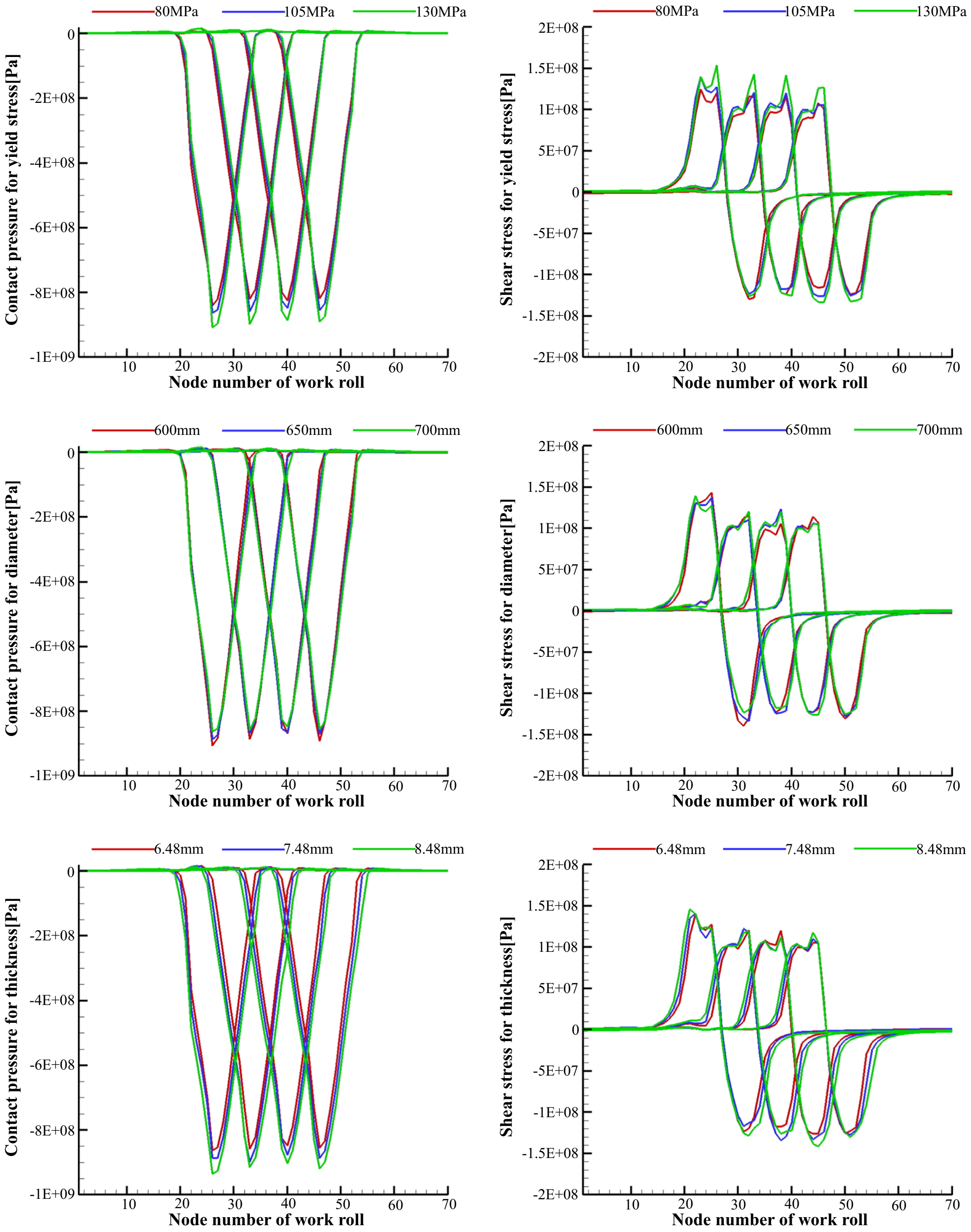

Fig. 6 Contact pressure and shear stress for various parameters in the contact area

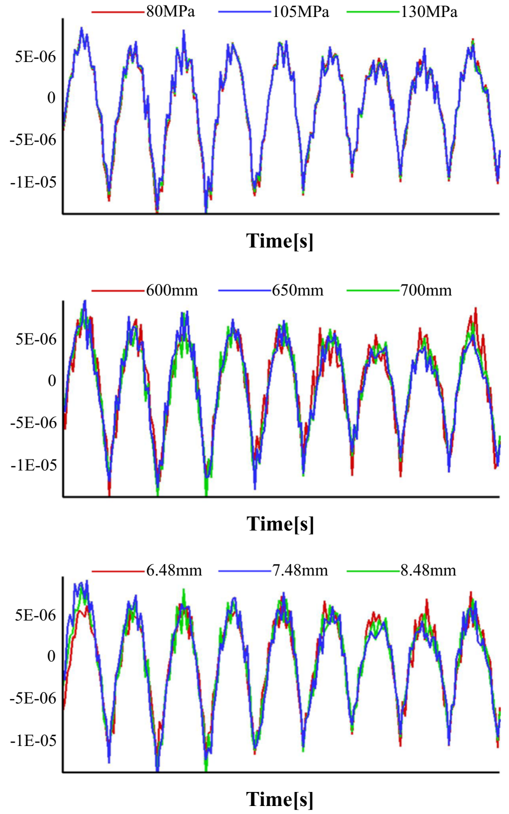

Fig. 7 Displacement of the WR center node from the average position for the rolling process parameters

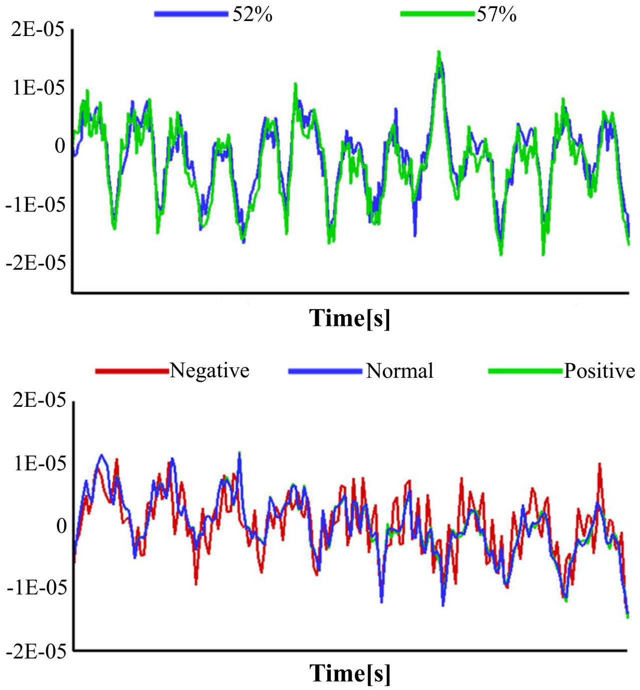

Fig. 8 Displacement of the WR center node from the average position according to the reduction ratio and COF gradient

the interface showed different results for the radius, thickness, and yield stress. However, similar trends in the vibration characteristics with regard to the center node position were observed. The results verified that the physical behavior (i.e., contact pressure and frictional stress) relative to the changes in the rolling process parameters did not directly affect the vibration characteristics. Numerical analysis was conducted by applying the COF negative gradient (boundary lubrication), positive gradient (hydrodynamic lubrication), and constant conditions to the same rolling process condition to verify the Stribeck curve effect. Meanwhile, experiments using a lubricant must be performed to determine the gradient size [G]. The numerical analysis, which was first used to determine the effects of the negative and positive gradients on the vibration characteristics, was conducted by setting arbitrary values. An equation applied in the Panjkovic study was employed for the COF equation applied to the contact area [8].

Figure 8 shows the vibration characteristics according to the gradient of the COF and the reduction ratio. The contact pressure increased (Fig. 5) with an increase in the reduction ratio. However, the 52% vibration characteristics and the 57% reduction conditions, where the chatter occurred, were similar. The numerical analysis results for the varying COF slopes revealed similar behaviors for the constant and positive slopes. The physical behavior for the negative slope was initially similar to that of the corresponding normal and positive slopes, but the vibration amplitude increased over time. This result indicated that the vibration characteristics were not directly changed by the differences in the contact pressure or the shear stress, which were themselves a result of the changes in the rolling process parameters. Instead, the changes in friction conditions at the interface, which resulted from the differences in the contact pressure and the shear stress, affected the vibration.

4 Discussion

4.1 Cause of chatter

To identify the causes of chatter, a numerical simulation was conducted as the rolling process parameters were varied. The simulation results verified that the contact pressure per work roll area increased by between 8 and 10% during strip manufacturing. From this result, the increased contact pressure was determined to be a cause of vibration (based on the Stribeck curve theory) [13]. In addition, the numerical analysis with varying COFs confirmed that a simple increase in the rolling force did not directly affect the vibration through the trace of the WR center node. Instead, vibration was induced by changes in the friction at the interface due to the increased rolling loads. More specifically, the existing strip manufacturing process involves a rolling process under hydrodynamic lubrication, in which the strip and work roll are completely separated (based on the Stribeck curve theory); however, the surfaces of the strip and work roll move close together due to the boundary lubrication effects that occur during thin strip manufacturing, resulting in intermittent contact between the projections on the interfaces. This not only increases the COF but also accelerates the work roll wear. Therefore, it is important to maintain hydrodynamic lubrication at the interfaces.

4.2 Limitations

This study examined the possibility of chatter occurrence caused by the increased rolling loads (based on the Stribeck curve theory). However, since chatter has complex causes, it is necessary to analyze other possible causes of chatter in addition to increased rolling loads. Since the specific numerical values of factors that influence the COF have yet to be defined, and since real rolling processing environments are not ideal (in contrast to the numerical simulations), it is not reasonable to compare the results from the numerical analysis with actual rolling results. In addition to including unit load factors, Stribeck curve theory also accounts for viscosity and speed factors. In particular, because the viscosity factor is related to the lubricant viscosity and iron oxide thickness, it is necessary to analyze changes in the lubrication conditions as a function of changes in the lubricant viscosity and iron oxide thickness. Because these changes are not easy to identify through numerical analysis, COF changes must be analyzed experimentally.

5 Conclusion

A gradual increase in the vibration size of the chatter could cause considerable damage to the rolling mills over time. This chatter interrupts processes and limits the number of continuous strip coils, thereby resulting in reduced CEM process productivity. The various causes of chatter (i.e., the regenerative effect, Stribeck curve, and lubrication) were investigated in this study. Moreover, the causes of the changes in COF curve gradient, where chatter occurred because of the contact pressure resulting from an increase in the reduction ratio, were estimated. A numerical analysis was also conducted for the factors (i.e., reduction ratio, yield strength, strip thickness, and work roll radius) affecting the increase in contact pressure in the rolling process. Subsequently, the contact pressure and the shear stress were analyzed, and the vibration characteristics were identified by tracking the WR center node position. The results revealed that the contact pressure increased according to changes in the rolling process parameters, but the vibration characteristics were constant. This result implied that an increase in the contact pressure did not directly affect the vibration, but influenced the contact area of the WR and the strip. We verified this through analysis of the vibration characteristics by applying a negative gradient (boundary lubrication), positive gradient (hydrodynamic lubrication), and constant conditions to the COF of the contact surface, following the Stribeck curve theory. The numerical analysis result indicated that the vibration characteristics were identical when the COF had a positive gradient and a constant, while the vibration amplitude was gradually increased when the COF had a negative gradient.

In summary, this study investigated the causes of an increase in magnitude of the vibration amplitude and a numerical analysis was conducted. Consequently, we have verified that an increase in contact pressure does not directly affect the vibration, and functions that include the physical behaviors of the COF of the contact area between the work roll and the strip should be applied to analyze changes in the vibration characteristics.

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