On-line Inter-stand Tension Monitor System for Bar Mill

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In wire rod and bar mills, it is important to optimize inter-stand tensions in order to prevent problems during rolling and to prevent dimensional variations in the longitudinal direction. The stabilization of inter-stand tension, however, has hitherto been dependent on the adjustment skills of operators. This paper relates to a method that was developed to estimate inter-stand tensions on the basis of a model for wire rod rolling. This model uses the values of motor current, which can easily and constantly be obtained during rolling without relying on the skills of the operators. A tension monitor system was newly developed to provide the rolling mill operators with inter-stand tension estimated in real time using the above method, and this monitor was introduced to the bar rolling mill at the Kobe Works of Kobe Steel. As a result, the system has facilitated the motor speed adjustment performed by the operators. This contributes to the stabilization of the inter-stand tension in actual operation and to the reduction of operational troubles.

Introduction

For the rolling of steel-bar products, it is important to maintain the inter-stand tensions between the stands of rolling trains within an appropriate range so as to prevent problems including rolling troubles such as cobbles, surface defects such as scab, and the dimensional variation of leading/tailing ends. In the case of steel bar rolling, only a certain type of stand can adapt a tension adjustment mechanism by loop control due to the size of the material being rolled. Hence, rolling mill operators adjust each inter-stand tension to an appropriate tensile/compressional state by manipulating the rotations of rolls. They determine the tension/compression of the material between the stands of rolling trains from the changes in the electric current of the main electric motor that drives the rolls during the process from the tension-free state on the exit side, when the tip of the rolling material is bitten, to the tension-loaded state on the exit side, when the tip is bitten into the next stand. There are, however, challenges in that the ammeter must be monitored while the material tip passes through, and that the change in electric current is instantaneous and difficult to recognize at the downstream stands where the rolling speed is high, which are not easy tasks for an operator with little operating experience.

The proposed methods for quantifying inter-stand tensions include a method[1)] of directly detecting the force acting on roll chocks in the rolling direction, and another method[2), 3)] involving the calculation of rolling torques from the rolling load measured by load cells to estimate tension. Each of these methods, however, requires a load cell, which complicates the equipment configuration, and the soundness of the sensors must be maintained.

Hence, Kobe Steel has developed a system to monitor and grasp tension more easily. This system not only allows less experienced operators to easily adjust the tension, but also can automatically read the changes in the driving current before and after the biting by the next stand, and, moreover, can estimate the tension values on the basis of a rolling model and display them. By referring to these values, the operators can easily adjust the rotational speed of rolls and stabilize the inter-stand tension. This paper outlines this tension monitor system for steel-bar rolling.

1. Outline of steel-bar rolling line

The steel-bar rolling line at Kobe Works of Kobe Steel consists of a heating furnace, a roughing train (8 stands), an intermediate train (4 stands), a finishing train (4 stands) and a block mill (5 stands) (**Fig. 1**). Billets of 155 mm square or 182 mm square are rolled into steel bars of ϕ17 mm to ϕ108 mm in diameter. A loop control mechanism is introduced between the intermediate train and the finishing

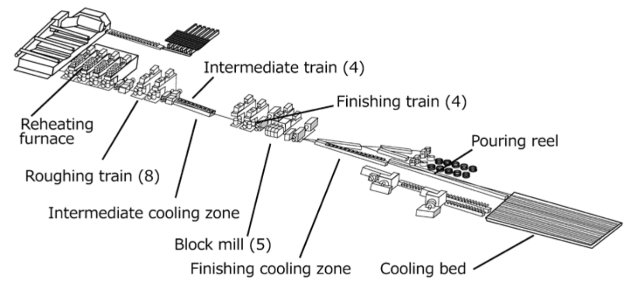

Fig. 1 Layout of bar mill in Kobe Works

train, and tension-free rolling is performed on the entry side of the finishing train. However, there is no loop mechanism for the trains further upstream. As a result, tensile force or compressive force may be exerted on the rolled material between adjacent stands, depending on the relationship between the rotational speeds of the rolls in them.

2. Development of tension monitor

2.1 Concept of tension monitor

In the continuous rolling of a steel bar, tension (tensile force or compressive force) is applied to the rolled material between the stand on the upstream side and the subsequent stand (on the downstream side) at the moment when the tip of the rolled material is bitten by the subsequent stand. Due to this inter-stand tension, the roll drive torque of the stand on the upstream side changes, causing a change in the motor current (differential current) in the motor that drives the rolls (**Fig. 2**). That is, when a tensile force occurs, the differential current of the motor on the upstream stand becomes negative, and when a compressive force occurs, it becomes positive. Hence, a roller operator memorizes the motor current value for the tension-free state before the tip of the rolled material is bitten by the subsequent stand and estimates the state of tension between the stands from the change in the motor current immediately after the biting to adjust the rotational speed. This adjustment method, however, requires continuous monitoring so as not to miss the change in the electric current value at the time of biting, and this interferes with other tasks such as monitoring the condition of passing material. Also, in the inter-stands with high rolling speed, the movement from one stand to the next is instantaneous, and it is difficult to visually recognize the differential current.

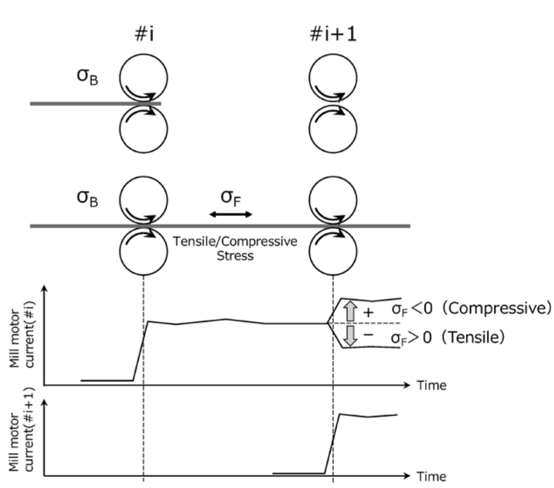

Fig. 2 Method of measuring inter-stand tension using difference of motor currents between #i and #i+1

Hence, Kobe Steel has constructed a system that allows easy adjustment of the rotations to obtain an appropriate tension by grasping the inter-stand tension, which is difficult to measure. In this system, the automatically detected change in motor load is converted into tension using a rolling model and is displayed in an easy-to-recognize manner.

2.2 Inter-stand tension model

A model for wire rod rolling was used as an analysis technique to estimate the tension from the differential current.[4)-6)] The rolling load, P_0, and rolling torque, G_0, in the tension-free state are calculated by the rectangle conversion method proposed by Saito et al:[4)]

$$P_0 = Q_P \cdot k_{fm} \cdot F_D \quad \cdots\cdots (1)$$

$$G_0 = 2\xi \cdot l_d \cdot P_0 \quad \cdots\cdots (2)$$

wherein Q_P, is the roll-separating force function; k_{fm}, average deformation resistance; F_D, projection area of contact; ξ, torque arm coefficient; and l_d, contact arc length.

Next, the rolling state under tension is calculated by the method proposed by Noguchi et al.,[5), 6)] and the rolling load, P, under tension is expressed by Equation (3):

$$P = P_0 \times \left(1 + a_1 \frac{\sigma_F}{k_{fm}} + a_2 \frac{\sigma_B}{k_{fm}}\right) \quad \cdots\cdots (3)$$

wherein P is the load (tension loaded); P_0, load (tension free); σ_F, forward tension; σ_B, backward tension; and a_1, a_2, influence coefficients.

The rolling torque (driving torque) G under tension is given by Equation (4):

$$G = G_0 \left\{1 + \frac{R_m}{G_0}(F_0\sigma_B - F_1\sigma_F)\right\} \quad \cdots\cdots (4)$$

wherein G_0 is the torque (tension load); R_m, average roll diameter; F_0, cross sectional area of material on the entry side; and F_1, cross sectional area of material on the exit side.

In wire rod rolling, the flow of material in the width direction is greater and expands the dimension in the direction orthogonal to the rolling direction after rolling (width expansion).

The relationship between the rolling conditions and the width expansion is expressed by Equation (5).[5)]

$$b = b_0 \left[1 - \frac{B}{b_0}\left(0.025 \frac{\sigma_f}{k_{fm}} + 0.769 \frac{\sigma_b}{k_{fm}}\right)\right] \quad \cdots\cdots (5)$$

wherein H and B are the material height and width, respectively, on the entry side; b_0, material width on the exit side (tension free); and h and b, material height and width, respectively, on the exit side (with tension loaded).

The width expansion is expressed by equation (6).

$$\Delta b = \frac{\partial b}{\partial \sigma_F}\Delta\sigma_F + \frac{\partial b}{\partial \sigma_B}\Delta\sigma_B \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \quad (6)$$

Equation (4) becomes $G = \mathrm{Func}(H, B, h, b, k_{fm}, \sigma_F, \sigma_B)$. Therefore, assuming that there is no change in the material dimensions on the entry side and deformation resistance before and after the biting, the change in rolling torque, ΔG, at the stand on the upstream side when the material is bitten by the next stand is given by:

$$\Delta G = \frac{\partial G}{\partial \sigma_F}\Delta\sigma_F + \frac{\partial G}{\partial \sigma_B}\Delta\sigma_B + \frac{\partial G}{\partial b}\Delta b + \frac{\partial G}{\partial h}\Delta h \quad \cdots\cdots\cdots \quad (7)$$

In hot rolling, the change in backward tension due to the change in forward tension is generally small, and, assuming that the change does not exist ($\Delta\sigma_B = 0$), the following holds:

$$\left.\begin{aligned} \Delta G &= \frac{\partial G}{\partial \sigma_F}\Delta\sigma_F + \frac{\partial G}{\partial b}\frac{\partial b}{\partial \sigma_F}\Delta\sigma_F \\ \therefore \Delta\sigma_F &= \Delta G \Big/ \left(\frac{\partial G}{\partial \sigma_F} + \frac{\partial G}{\partial b}\frac{\partial b}{\partial \sigma_F}\right) \end{aligned}\right\} \quad \cdots\cdots\cdots\cdots\cdots\cdots \quad (8)$$

From the relational equation between the rolling torque and drive motor current, $G = \eta VI/(2\pi N)$, Equation (8) is expressed as Equation (9):

$$\Delta\sigma_F = \left(\frac{\eta V \Delta I}{2\pi N}\right) \Big/ \left(\frac{\partial G}{\partial \sigma_F} + \frac{\partial G}{\partial b}\frac{\partial b}{\partial \sigma_F}\right) \quad \cdots\cdots\cdots\cdots\cdots\cdots \quad (9)$$

wherein V is the rated voltage of the motor; N, rotational speed of the motor; I, motor current; ΔI, differential current; and η, efficiency.
The partial derivatives, such as $(\partial G/\partial \sigma_F)$, are calculated in advance by numerical differentiation of the torque model equation (4) as in the example of Equation (10).

$$\frac{\partial G}{\partial \sigma_F} = \frac{G(\sigma_F + \Delta\sigma_F) - G(\sigma_F - \Delta\sigma_F)}{2\Delta\sigma_F} \quad \cdots\cdots\cdots\cdots\cdots \quad (10)$$

From Equation (9), the inter-stand tension $\Delta\sigma_F$ can be estimated from the change in the electric current ΔI when the material is bitten by the next stand.

Fig. 3 shows the flow of the model for calculating the inter-stand tension using the above equations. As described, by combining conventionally proposed equations while assuming that the mill rigidity is large and there is no tension propagation from the downstream side to the upstream side stand, the inter-stand tension is obtained by a simple equation.

2.3 Processing of current values and examples of inter-stand tension calculation

As an example of obtaining the inter-stand tension described in Section 2.2, **Fig. 4** shows the electric current data during actual rolling. Fig. 4 (a) is a case where the inter-stand tension is compressive. First, the load begins to be applied to the motor when the rolled material is bitten by the #i stand (here, i = 1). It is shown that, when the rolled material is bitten by the #(i+1) stand on the downstream side at a later time, the current value of the #i stand increases stepwise, increasing the motor load of the #i stand. The current value of the motor for the tension-free state ((A) in Fig. 4 (a)) is acquired

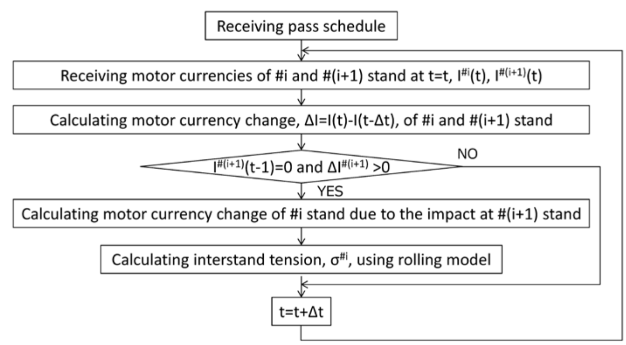

Fig. 3 Flow of calculating inter-stand tension

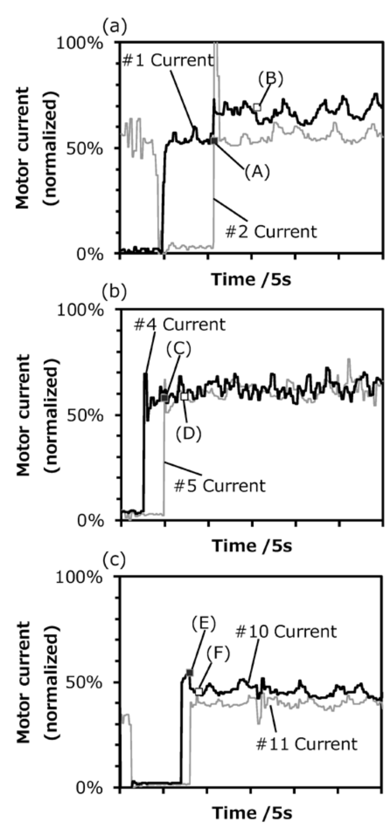

Fig. 4 Example of detection of inter-stand tension (detected stress of (a); compression, (b); neutral, (c); tension)

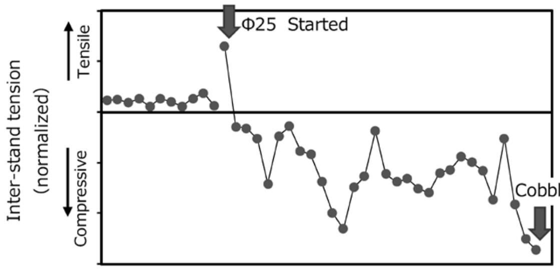

Fig. 5 Inter-stand tension between #10 and #11 stands in cobbling

at the moment when the rolled material is bitten by the #(i+1) stand. Let this current value be I_A. The motor current value after the biting by #(i+1) stand is obtained when a certain time has elapsed after the biting by #(i+1) stand ((B) in Fig. 4 (a)).

Let this current value be I_B. On the basis of the difference between the two current values ($\Delta I = I_A - I_B$), the inter-stand tension is calculated by the method described in the previous section. It should be noted that I_A is the average current value of several points before the biting by #(i+1) stand. Similarly, I_B is the average current value of several points after the biting by #(i+1) stand. The acquisition timing of I_A and I_B was optimized for each stand and line speed, excluding the moment of impact. Such processing has enabled the estimation of reasonable tensions from the current values with large fluctuations.

Fig. 4 (b) shows a case where #i-# (i+1) inter-stand tension is almost 0 (in this case, i = 4), and (c) shows a case where #i-# (i+1) inter-stand tension is tensile (i = 10 in this case). In these figures, (C) and (E) are just before the biting by the next stand, and (D) and (F) are the electric current values of # 4 and # 10 stands after the biting and their acquisition timing, respectively. In either case, this technique has been confirmed to stably detect proper motor current values.

In order to confirm the validity of this technique, the transition of tension was examined for the case where cobble occurred due to poor adjustment of the rotational speed (**Fig. 5**). In Fig. 5, the product dimension rolled for the 12th run is changed to Φ25 mm, at which time the hole type of the rolls was changed (type setting). At the 30th run after the type setting, the compressive force increased between the #10 and #11 stands, causing buckling and cobbling. The transition of tension during this period indicates that the tension between the #10 and #11 stands after type setting has shifted to the compressive direction. It is conceivable that, if the worker could recognize that such a compressive stress state is continuing, the cobble caused by buckling would have been avoided.

3. Overview of tension monitor system

Fig. 6 shows the configuration of the constructed tension monitor system. The monitor system acquires rolling command information from the process computer, and also acquires the motor speed and current value for each stand from the controller. The inter-stand tension model described in Section 2.3 is implemented in the monitor system, which calculates the forward tension at the upstream stand immediately after the material is bitten by the next stand. When one of the inter-stand tensions is renewed, the monitor system replaces the tension value displayed on the tension monitor screen (operator assistance screen shown in **Fig. 7**) with the latest one. The assistance screen displays the most recent 20 tensions along with the inter-stand tensions of the material currently being rolled (bottom of the screen). In addition, the past results of inter-stand tension for the same size are displayed as a histogram (middle of the screen), making it easier for the operator to determine whether the current tension state is appropriate. These past results for the tension are updated sequentially.

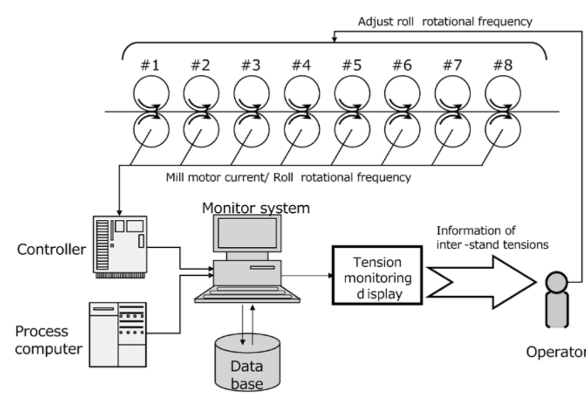

Fig. 6 System configuration for monitoring inter-stand tension of bar rolling mill

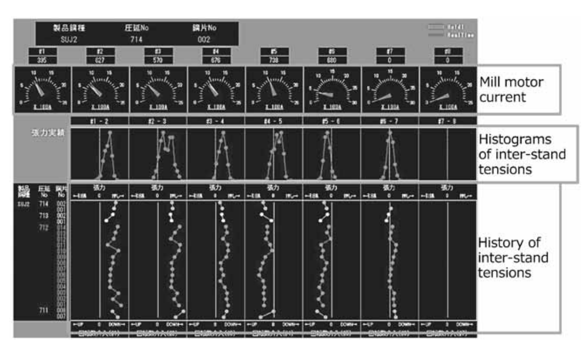

Fig. 7 Monitor image of inter-stand tension for operator

4. Results of tension monitor system application

This tension model was incorporated into a tension monitor system, which comprises an achievement collection function and a screen display function, and the system was launched. **Fig. 8** shows the transition, after the introduction of this system, of the variation in the tension actually applied after being calculated by this system. The target product types were: a) Φ30 mm bearing steel and b) Φ23-27 mm cold heading steel, both with large rolling reductions. For each rolled material, the standard deviation of the tension value obtained at each inter-stand for #1 to #5 was calculated every 3 months. At this time, the results were standardized assuming the standard deviation of tension between # 2 and # 3 in 2012 1Q to be 1.

Although there are differences depending on the stands, the standard deviation of the measured tension values has decreased since 1Q, i.e., during 2Q to 4Q, immediately after the introduction. Conventionally, operators observed the change in the current value when a rolled material was bitten to measure the timing for adjusting the rotations as the material passed each stand. The introduction of the tension monitor system has enabled the current values to be displayed as calculated tension values on one screen and be displayed also as a trend in the order of rolling. It is perceived that this has enabled the operators to grasp the situation of multiple stands at a glance with any timing and has felicitated the adjustment of the rotational speed, which has led to the stabilization of inter-stand tension.

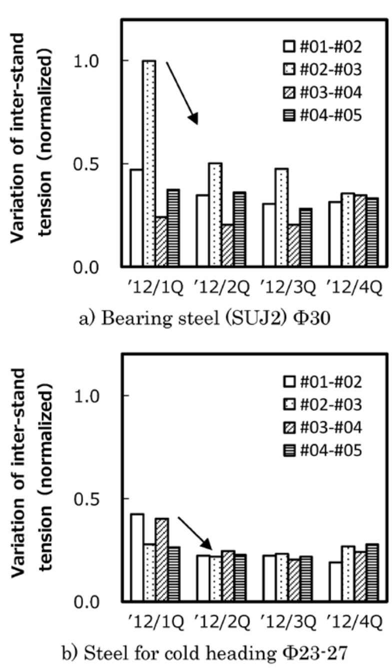

Fig. 8 Changes of inter-stand tensions

Fig. 9 shows the cobble frequency before and after the introduction of this tension monitor system. The frequency of occurrence was tabulated every 3 months and standardized with the maximum occurrence frequency as 100%. Cobble is known to occur due to various reasons, including improper adjustment of the roll speed, and has decreased significantly since the application of the monitor system.

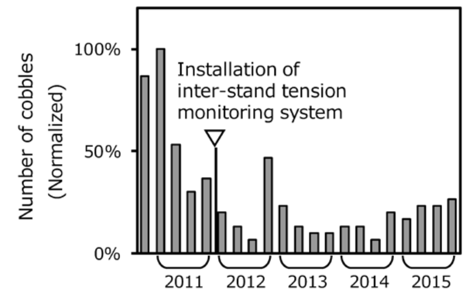

Fig. 9 Changes in number of cobbles in bar mill

Conclusions

A technique was developed to calculate the inter-stand tension from the differential current using a steel-bar rolling model. A tension monitor system that displays the tension calculated by this technique was introduced into the steel bar plant of Kobe Works, Kobe Steel. This monitor system is used by the operators to adjust the rotational speed of the rolling train motor, and, as a result, variations in tension setting have been reduced, contributing to the reduction of cobble.

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