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Measurement of the forward slip in cold strip rolling using a high speed digital camera

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Abstract

The forward slip in strip rolling was defined as the relative difference between the roll surface speed and strip exit speed. It was always an important parameter because of its significant influence on friction and tension control. In this study a Phantom V3.0 digital high speed image acquisition and motion analysis system was used to record the movement of the roll and the workpiece during rolling. The pictures captured were analyzed to obtain the speeds of the roll and the workpiece along the roll bite, which then yielded the forward slip. The measurement accuracy has been validated by the mass conservation. The maximum relative error of the forward slip was only 1.6 %. The results have shown that the forward slip increased as the reduction increased for both dry and lubricated rolling. The roll speed did not change the forward slip in the case of dry rolling, but the forward slip was significantly reduced with roll speed when lubricated.

Keywords: Strip cold rolling; Forward slip; High speed camera

1. Introduction

Since the initial thickness of the strip is reduced during cold strip rolling, the exit speed of the strip from the roll bite must be higher than the entry speed due to the mass conservation. In a steady rolling process, the strip enters the roll bite at a speed slower than that of the rolls, while the exit speed is faster. At a certain point in the roll bite, which is know as a neutral point, the strip and the rolls move at the same speed. Before the neutral point, the frictional force drags the strip into the roll bite. Beyond the neutral point, the frictional force operates in an opposite direction and tries to prevent the strip from leaving the roll bite. As well known, the relative speed between the strip and the roll plays a significant role on friction. The forward slip defined below is used to indicate the relative movement between the strip and the roll;

$$S_f = \frac{V_s - V_r}{V_r} \quad (1)$$

where S_f is the forward slip, V_r the roll surface speed, V_s the strip speed at the roll bite exit.

The forward slip is always an important parameter in cold strip rolling because: (1) A complete understanding of friction in strip rolling is still lacking due to the complexity of friction phenomenon and the difficulty of the measurement. The usual method to evaluate friction is so-called inverse method, in which the average coefficient of friction is adjusted to match the measured and predicted rolling force. As pointed out by McConnell and Lenard [1], more measured parameters are used, the more accurate the method is likely to be. Except for the rolling force and roll torque, the forward slip is another parameter which can be measured in both industrial and experimental

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environment. Lenard and his co-workers have predicted a more accurate coefficient of friction via matching all of the measured rolling force, roll torque and forward slip with their predicted values. The accurate forward slip measurement will improve the friction determination. (2) In tandem cold mill, the tension is adjusted through changing the difference between the strip exit speed at the previous stand and the strip entry speed at the next stand. Both speeds are calculated based on the forward slip. Therefore, the accurate forward slip model is essential to the tension control, and in turn the final product quality.

Several techniques have been used to measure the forward slip. One of them is the marking method [2-4]. Two parallel fine lines are marked on the work roll surface. After the roll turns one revolution, two marked lines leave their imprints on the strip surface. The forward slip can be evaluated by comparing the distance between the two marked lines and the distance between two imprints. Another method is to measure the roll velocity and the exit velocity of the rolled strip [1]. A shaft encoder monitors the rotational velocity of the roll. Two photodiodes are positioned at the exit, a certain distance apart. The moving strip head stops the light shining on the first diode and then on the second. The time difference between their signals provides the exit speed and hence the forward slip. Laser doppler velocimetry (LDV) has also been used in the measurement of the forward slip [5].

There are two demands for the measurement of the forward slip. The first one is the measurement accuracy; the second one is instantaneous measurement. The accuracy of the forward slip measurement is always a challenging problem. The roll surface speed and the strip exit speed are two nearly equal values. From the definition of the forward slip, it is easy to note that even a very small error in one measured value leads to a significantly larger error in the forward slip. Therefore, the forward slip measurement requires very high measurement accuracy for both speeds. In the marking method, the imprint line become wider and blurry with increasing reduction, which results in the poor accuracy. The measurement accuracy of photodiodes in the second method mentioned above is also limited. Both two methods only provide an average forward slip and the second method measures the unstable rolling period, during which the roll speed slows down and friction is different with the stable rolling period. Even though the LDV method can provide an instantaneous high-accuracy forward slip measurement, it is sophisticated to apply. In this paper, a high speed digital camera is used to measure the forward slip. The high measurement accuracy will be proven. The effects of the rolling process parameters on the forward slip are discussed.

2. Speed measurement

A Phantom V3.0 digital high speed image acquisition and motion analysis system was used to determine the speed of the rolled workpiece and the roll during cold rolling. The Phantom system integrated a high-speed digital camera, a compact computer and an image capture and analysis software. The high-speed digital camera had 512 512 pixel resolution and anti-blooming CCD array. Up to 500 pictures per second (pps) could be recorded. The computer had 256 megabyte memory, which allowed 2 seconds continuous recording for full picture at 500 pps and longer recording time for lower samples rates and allocated picture formats. In this work, eight seconds recording time at 500 pps could be obtained since only one fourth of full picture, surrounding the roll bite, needed to be recorded. Eight seconds could cover the rolling time of all the workpieces rolled. The Phantom software had the functions of image-with-data capture, image playback, image processing and measurement tools. This software was used to measure the speed of both the workpiece and the roll.

To obtain high quality pictures, sufficient lighting and maximum magnification were parameters to be considered. A 2000 w spot light was chosen as an illumination device. The position of the spot light was carefully adjusted to guarantee an optimum intensity of light. A wide-angle lens was used to provide a large magnification. The clear pictures could be captured when the lens was located at the position 1125mm from the operating side edge of the roll. A typical picture is shown in Fig. 1.

In the Phantom software, the distance directly measured from the picture was the pixel distance (number of pixels). To transform the pixel distance to the actual distance, the calibration procedures were necessary. A ruler was placed at the position of the side faces of the workpiece. A distance by the scale of the ruler could be read, and then the function provided by the software was used to setup the relationship between the pixel distance and the actual distance.

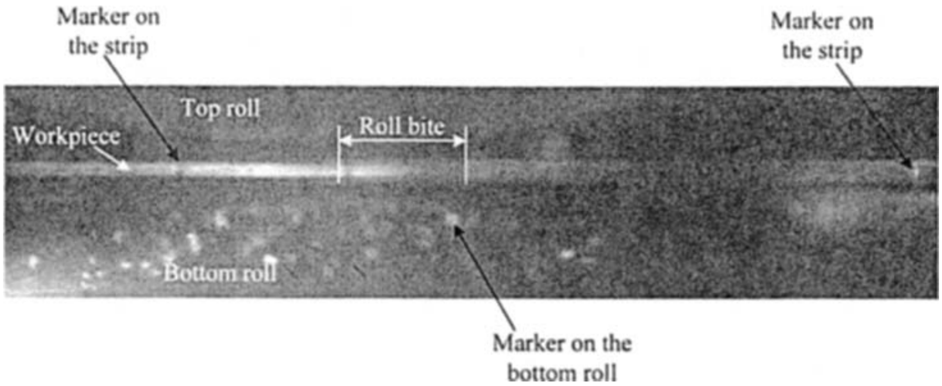

Fig. 1. A typical picture captured by the high speed digital camera.

To calculate the speed, two types of markers were made on the side face of the workpiece and the bottom roll. On the side face of the workpiece, the lines were marked. The measured points were assigned to the center of each line marker. On the side face of the roll, the line markers were not used since it became blurry when the image was focused on the side face of the sample. We sprayed oil to the side face of the bottom roll. The round oil droplets were attached on the roll side face and used as the markers. The measured points were assigned to the center of each round oil droplet marker.

The positions of the measured points were calculated for all the pictures. The displacement (ΔS) of the measured point between two adjacent pictures could be obtained by using the coordinates in the first frame (x^i, y^i) and that in the second frame (x^{i+1}, y^{i+1}), namely

$$\Delta S = \sqrt{(x^{i+1} - x^i)^2 + (y^{i+1} - y^i)^2} \quad (2)$$

where i is the number of the picture. Since the interval time (ΔT) between two adjacent pictures was known, the speed could easily be obtained by $V = \Delta S / \Delta T$.

The measurement error caused scatter in the raw data, especially for high speed case. The filters were adopted to reduce scatter. The measured positions of the roll marker are shown in Fig. 2. A second order polynomial was used to fit the raw data. The regressed positions (A' and B') were used to determine the displacement ($\Delta S_{A'B'}$) instead of the measured positions (A and B). The marker speed (V_m) was determined by

$$V_m = \frac{\Delta S_{A'B'}}{\Delta T} \quad (3)$$

Since there was a distance (Ds) between the roll surface and roll marker, the speed of the roll surface could be calculated by

$$V_R = V_M \frac{R}{R - D_s} \quad (4)$$

where V_R is the speed of the roll surface and R the roll radius. Ds was measured from Fig. 1.

The measured roll surface speed and workpiece speed are shown in Fig. 3. The solid cycle symbols represent the measured roll surface speeds, the solid square symbols for the measured workpiece speeds. A linear line and a sigmoidal curve are used to fit the measured data. The roll surface speed slightly increases with distance. The average value (V_R^{ave}) of the measured roll surface speed will be used in the calculation of the forward slip. The workpiece moves at nearly a constant speed before entering the roll bite. The speed starts to increase when the measured point reaches the roll bite entry. In the roll bite, the workpiece speed, as expected, increases due to the reduction of the workpiece thickness. At the neutral point, the workpiece speed reaches the roll surface speed. And then the workpiece moves faster than the roll. The workpiece remains a constant speed once leaving the roll bite. The sigmoidal curve of the workpiece speed has two limiting values in Fig. 3. The workpiece entry speed (V_{entry}) and exit speed (V_{exit}) correspond to two limiting values, respectively. For the lubricated rolling case, the workpiece exit speed could not be measured since the markers at the roll bite exit region were covered by the oil exacted from the roll-workpiece contact interface. The workpiece exit speed was deduced from the entry speed by the equation: $V_{exit}=V_{entry}$ *H/h, where H

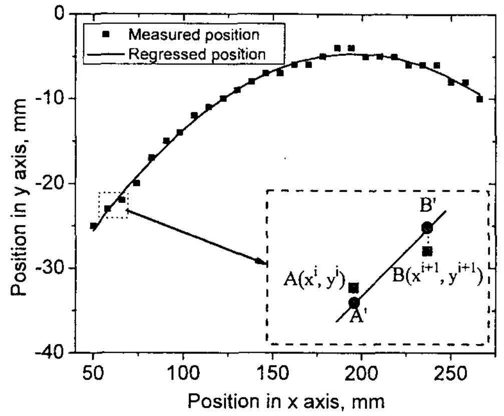

Fig. 2. Measured roll marker position.

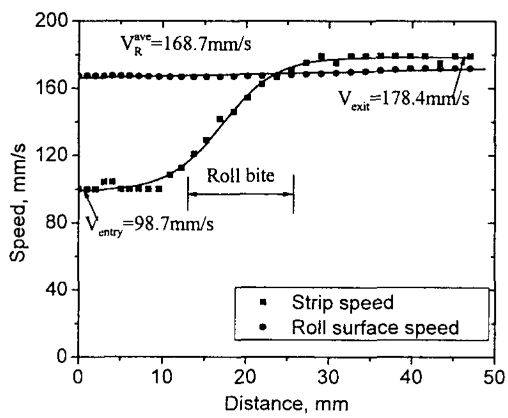

Fig. 3. Measured speeds of the rolled workpiece and roll.

and h are the measured entry thickness and exit thickness of the workpiece. Finally, the forward slip could be calculated using the measured V_R^{ave} and V_{exit}.

3. Experiments

A Hille 100 two-high experimental rolling mill was used to conduct the experiments. The mill was driven by an infinitely variable speed motor of 56 kW. The maximum rolling load, torque and speed were 1500 kN, 13 kNm and 70 rpm, respectively. The rolls were designed with 225 mm diameter and 254 mm barrel length, made of Böhler W302 tool steel. The roll surface was treated by the nitride hardening and its hardness was 65 to 70 HRc within a depth of 0.2-0.3 mm. The roll surfaces had been ground and the roughness was Ra=0.35 μm along the circumferential direction and Ra=0.38 μm along the axial direction. The roll gap could be set by a mechanical screwdown system and two hydraulic capsules.

Two strain gauge load cells were installed between top roll chocks and screws on operating side and drive side to measure the rolling force. Two strain gauge torque transducers were placed in the drive spindles to measure the rolling torques of both top and bottom rolls. The signals of the rolling force and torque were recorded by a digital data acquisition system including a computer, an amplifier and a data acquisition board. A position transducer, LVDT, was mounted on the roll chocks to monitor the roll gap.

The rolled workpieces were Aluminium alloy 6060-T5. The worpiece was cut parallel to the original rolling direction, having the dimension of 2.88 mm x 100 mm x 1000 mm (thickness x width x length). The initial surface roughness of the samples was Ra= 0.22 μm along the rolling direction and Ra= 0.24 μm along the transverse direction.

Caster oil was used as lubricant. The kinematic viscosity was 0.3 Pas at 30°C and 0.08 Pas at 60°C. The pressure-viscosity coefficient was 15.9×10^{-9} m^2/N at 30°C and 14.4×10^{-9} m^2/N at 60°C.

Prior to each rolling pass, the roll and workpiece surfaces were cleaned by acetone and the roll gap and speed were set to the required setting. The lubricant was brushed evenly on both surfaces of the workpieces for tests under lubricated conditions. The digital camera system and the data acquisition system were started when the workpiece was pushed to the roll bite. During rolling, the data of the rolling force and rolling torque were collected, and the pictures of the roll and the workpiece near the roll bite were recorded. After rolling, the pictures captured by the digital camera were analyzed to obtain the speeds of the roll and the workpiece, which then yielded the forward slip.

4. Results and discussion

According to the mass conservation, the mass flow through each cross section of the workpiece in the roll bite should remain constant. The width change can be negligible in cold strip rolling. Therefore, we have

$$HV_{entry} = hV_{exit} \tag{5}$$

Namely

$$\frac{H}{h} = \frac{V_{exit}}{V_{entry}} \tag{6}$$

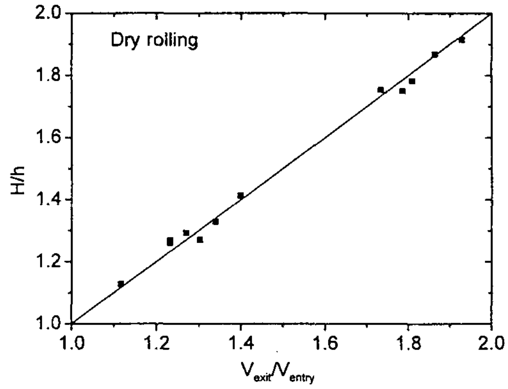

Fig. 4. Measured H/h against measured V_{exit}/V_{entry}.

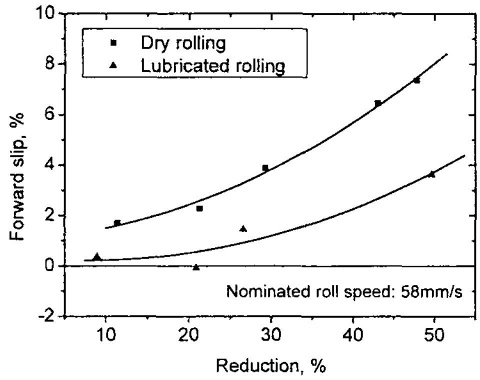

Fig. 5. Relationship between the forward slip and reduction.

To validate the accuracy of the measured speed, H/h against V_{exit}/V_{entry} is plotted in Fig. 4. The entry thickness (H) and exit thickness (h) were measured by micrometer. V_{exit} and V_{entry} are the measured exit speed and entry speed of the workpiece respectively using the high speed digital camera. The figure shows that two values are in very good agreement. The maximum relative difference is only 1.6 %, which indicates that the accuracy of the measured speed is reliable.

Reduction and roll surface speed are two major rolling process parameters. The effects of the reduction and roll surface speed on the forward slip for both dry rolling and lubricated rolling are plotted in Figs. 5-7. In these figures, the forward slip in percentage is given on the ordinate, and the reduction in percentage or roll surface speed in mm/s is given on the abscissa. The solid symbols represent the measured forward slip. The second-order polynomial curves are used to fit the measured data and indicate the trends.

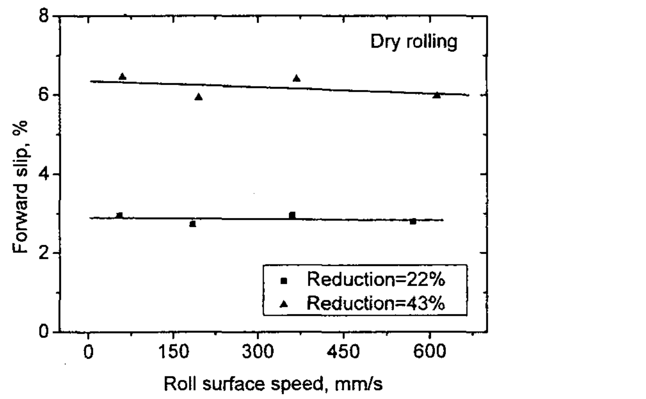

Fig. 6. Relationship between the forward slip and roll surface speed during dry rolling.

Fig. 5 shows the forward slip as a function of the reduction, varying from about 10 % to about 50 %, at a nominal roll surface speed of 58 mm/s. Two curves describe the dry rolling case and the lubricated rolling case, respectively. It can be seen that the forward slip increases as the reduction increases for both cases, except for the lubricated rolling at 21 % reduction. The forward slip is enhanced from 1.69 % to 7.38 % and from 0.32 % to 3.64 % for the dry rolling and lubricated rolling, respectively, when the reduction is increased from about 10 % to about 50 %. This observation suggests that the effect of the reduction on the forward slip is pronounced. The upward concave curves in Fig. 6 indicate that the slope or change rate of the forward slip in terms of the reduction ($\partial S_f / \partial \varepsilon$) is progressively increased with increasing reduction. Comparing two curves, it is noted that the lubricated rolling has a lower forward slip as well as a lower slope. The forward slip drops from 1.69 % to 0.32 % at a low reduction of about 10 %, and drops from 7.38 % to 3.64 % at a high reduction of about 50 % when the lubrication is introduced. The use of the lubricant results in the change of the coefficient of friction. Therefore, it can be concluded that the coefficient of friction affects the forward slip in a significant manner.

The forward slip versus the roll surface speed for two reductions of 22 % and 43 % without lubrication are presented in Fig. 6. It is noted that the roll speed does not change the forward slip significantly in the case of dry rolling of aluminum. The forward slip slightly decreases with increasing roll speed. It varies from 6.47 % to 5.98 % at the reduction of 43 % when the roll speed increases from 50 mm/s to 600 mm/s.

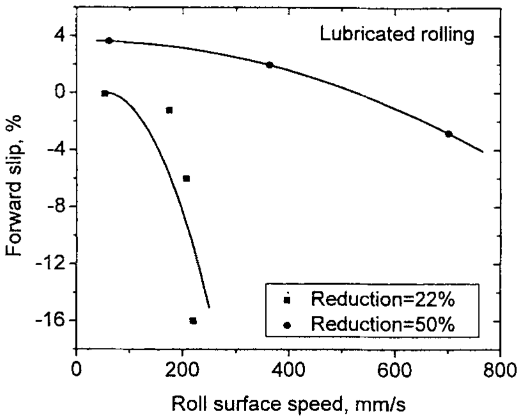

Fig. 7. Relationship between the forward slip and roll surface speed during lubricated rolling.

At low reduction, the variation of the forward slip with the roll speed seems to be negligible. The rolling speed only affects the coefficient of friction since the rolled material is strain rate independent. It can be concluded that the dependence of the coefficient of friction on rolling speed is limited during the dry rolling. The nearly linear curves in the figure also indicate that the roll speed does not affect the rate of change of the forward slip again the roll speed ($\partial S_f / \partial V_R$) in any significant manner. But increasing reduction leads to a much higher $\partial S_f / \partial V_R$.

The effect of the roll surface speed on the forward slip at the presence of lubricant is shown in Fig. 7. Two sets of results are plotted, one for nominal reduction of 22 %, another one for nominal reduction of 50 %. It can be seen that the roll surface speed has a significant influence on the forward slip. The forward slip is decreased as the speed increases for both curves. The curves are downward concave curves. At 22 % reduction, all the forward slip results are negative, indicating that the neutral point has moved outside the roll bite, and the values change drastically. When the roll surface speed is increased from 51 mm/s to 220 mm/s, the forward slip drops from -0.03 % to -16.2 %. It is expected that the mixed film lubrication or even hydrodynamic lubrication occurs as the speed increases. Beyond 220 mm/s, the workpiece fails to feed in the roll bite, namely the workpiece sliding happens. At 50 % reduction, the speed effect is less pronounced than 22 % reduction. The magnitude of the slope becomes smaller as the reduction increase.

5. Conclusion

An approach using the Phantom V3.0 digital high speed image acquisition and motion analysis system was developed to measure the forward slip in a cold strip rolling of aluminum. The experiments have been conducted with a Hille 100 two-high experimental rolling mill. The measurement accuracy has been validated by the mass conservation. The maximum relative error was only 1.6 %. The effects of the reduction and roll speed on the forward slip were investigated. The results have shown that the forward slip increased as the reduction increased for both dry and lubricated rolling. The roll speed did not change the forward slip in the case of dry rolling, but the forward slip was significantly reduced with roll speed when lubricated.

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