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Adjustment of Roll Gap for the Dimension Accuracy of Bar in Hot Bar Rolling Process

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ABSTRACT

The objective of this study is to adjust the roll gap for the dimension accuracy of bar in hot bar rolling process considering roll wear. In this study hot bar rolling processes for round and oval passes have been investigated. In order to predict the roll wear, the wear model is reformulated as an incremental form and then wear depth of roll is calculated at each deformation step on contact area using the results of finite element analysis, such as relative sliding velocity and normal pressure at contact area. Archard's wear model was applied to predict the roll wear. To know the effects of thermal softening of DCI (Ductile Cast Iron) roll material according to operating conditions, high temperature micro hardness test is executed and a new wear model has been proposed by considering the thermal softening of DCI roll expressed in terms of the main tempering curve. The new technique developed in this study for adjusting roll gap can give more systematically and economically feasible means to improve the dimension accuracy of bar with full usefulness and generality.

Keywords : Roll wear, Hot rod rolling, Thermal softening, Roll gap, Neural network

1. Introduction

In continuous hot rod rolling process, billets are processed into rods with acceptable dimensional tolerance as they pass through the rolling stands, with the cross sectional shape being progressively altered by the roll groove. Thus, the roll wear has been recognized as one of the most important process factors because differences in wear along the roll groove shape in the different stands decrease roll life and affect the dimensional tolerance of final product. This leads a process designer to focus on how to make a model for predicting the wear profile of (work) rolls over a range of rolling conditions.

The theory of wear can be classified according to the contacting conditions. Amongst the wear theories the abrasive-wear theory has been generally applied to the die-wear mechanism in various metal forming process. The abrasive-wear theory was suggested first by Holm [1] who introduced an experimental equation for studying the wear mechanism between two electrical contacting materials. Following Holm's suggestion, Archard [2] introduced macro-models of the wear phenomenon, proposing that the wear phenomenon is the collapse of micro-asperities on the two contacting bodies. Liou [3] applied the Holm's wear model to the high speed hot upsetting process and analyzed the die wear with the hardness of die as a function of die temperature. Hansen [4] used Archard's wear model in upsetting process and suggested that a rough die surface giving high friction causes a large reduction of the sliding length and thereby less wear. Kim [5] calculated die wear in the wire drawing process. They considered the hardness of die as a function of die temperature. Sachs [6] examined a series of work regarding the back up roll wear profiles at production mills. Williams [7] reiterated the significant wear effects due to the abrasive action of the formed three iron oxides. Ohnuki [8] showed that in the early revolution cycles where the abrasive wear is more effective, the greater the rolling load is, the larger the wear loss is. To evaluate of roll wear, Lundberg [9] designed the high-temperature test rig and put into operation. Park [10] conducted hot-rolling simulation test using a high-temperature wear tester capable of controlling speed, load, and temperature. They demonstrated that the HSS roll containing a larger amount of vanadium had the best wear resistance because it contained a number of hard MC-type carbides. In spite of the above concluding remarks, the quantitative studies to provide an applicable equation for the prediction of wear profile are limited in little factual information.

Experience in mill yard have shown that roll wear rate increases rapidly after production of a specific amount of rolled steel. The diversity in temperature, pressure and stress fields, along with sliding velocity gradient in caliber rolling result in accelerated wear of grooved rolls, but no quantitative study for predicting wear profile of roll has been reported yet.

The objective of this study is to adjust the roll gap for the dimensional accuracy of rod in hot rod rolling process considering roll wear using ANN (Artificial Neural Network). To do this, a modified Archard's wear model has been proposed by considering the thermal softening of DCI roll expressed in terms of the main tempering curve.

2. Experiments

2.1 Wear test

A wear test has been performed using a pin-on-disk type hot wear tester (Fig. 1). Table 1 shows the compositions of the conventional DCI roll used as the pin and low carbon steel (SM10C) with a chemical composition of Fe:0.1, C:0.45, Mn:0.25, Si (wt.%) was used as the disk. With due regard to the operating conditions in actual hot rod rolling process, experimental conditions were set up and wear coefficient for DCI roll was 8.096×10^{-6}.

2.2 Thermal softening test

Thermal softening related to time and temperatures was measured using a *High Temperature Micro Hardness Tester* (QM-2, Nikon Co.) for conventional DCI roll. Size of specimens is 5mm x 5mm x 10mm. Fig. 2 shows the inside view of high temperature micro hardness tester and high temperature hardness of specimen is measured on hot metal.

Table 1 The qualities of DCI roll

Mechanical Properties		*Chemical Compositions (%)*	*Heat Treatment*
Tensile strength (kg/mm^2)	*35-55*	*C: 3.20 – 3.60*	
Elongation (%)	*0.2-0.5*	*Si: 1.40 – 2.20*	
		Mn: 0.30 – 0.60	*Stress Relief*
Impact Value ($kg\text{-}m/cm^2$)	*0.2-0.5*	*Ni: 1.60 – 2.30*	
		Cr: 0.30 – 0.80	
Hardness (Hv)	*405*	*Mo: 0.20 – 0.60*	

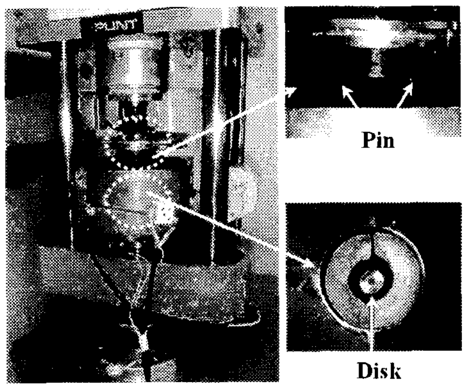

Fig. 1 Wear tester (PLINT, TE92)

From the results of thermal soften test, we can express tempering parameter, M, dependent on heat treatment, as follows [11].

$$M = T_s(20 + \log t_s) \tag{1}$$

where, t is tempering time (h) and T is the tempering temperature (K). The variation of hardness of DCI roll can be expressed using the tempering parameters as follows:

$$H_v = (A - B)/\{1 + \exp[(M - C)/D]\} + B \tag{2}$$

where, A, B, C and D are roll softening constants. Fig. 3 illustrates the approximated tempering curve for DCI roll. Roll softening constants for A, B, C and D are 287.29, –1125.74, 22.0 and 1.81, respectively.

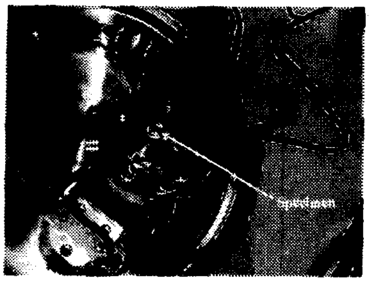

Fig. 2 Inside view of high temperature micro hardness tester

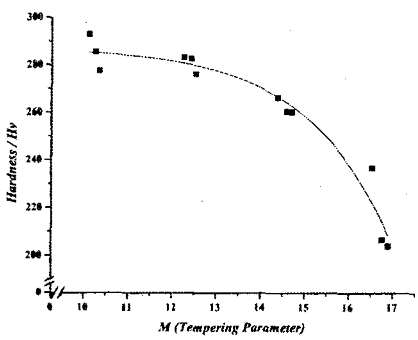

Fig. 3 Master tempering curve for DCI roll

3. FE-simulation for hot bar rolling process

Three-dimensional FE-analysis was conducted using a commercial FE code, DEFORM for a two-pass round-oval pass bar rolling sequence. The process conditions and design parameters for a two-pass rolling sequence are described in Table 2 and Fig. 4. The feature of specimens is a round bar with 60mm in diameter and 300mm in length. The friction factor between the work rolls and the workpiece was assumed to be 0.7 [12]. Initial temperature of roll and temperature of billet have

Table 2 The conditions of FE-simulation

Conditions	*1st pass*	*2nd pass*
	Round-oval	*Oval- round*
Specimen temp. (℃)	*1100*	*1100*
Roll temp. (℃)	*300*	*300*
Specimen diameters (mm)	*60*	-
Roll diameter (mm)	*320*	*320*
Roll gap (mm)	*6.5*	*6.5*
Rolling speed	*34rpm*	*34rpm*
Friction factor ($0 \leq m \leq 1.0$)	*0.7*	*0.7*
Lubricant	*No lubricant*	*No lubricant*

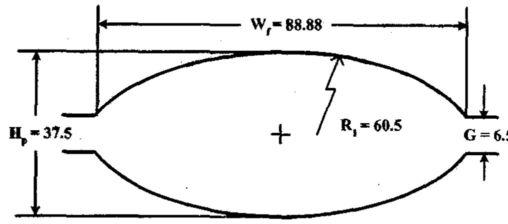

Fig. 4(a) Roll grooves of round-oval pass

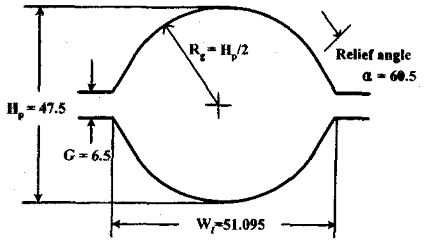

Fig. 4(b) Roll grooves of oval-round pass

been assumed as 300 and 1100°C, respectively. The flow stress of material (SM10C) was calculated by Shida's constitutive equation [13].

Finite element simulations have been performed for the two-pass rolling sequence until the deformation reaches steady state. Area reduction of round-oval pass is 39.2% and area reduction of oval-round pass is 20%. To examine the validity of finite element simulation, a single stand two-high laboratory mill was employed, driven by *75kW* constant torque, DC motor.

Ductile cast iron rolls were used, with 310*mm* maximum diameter and 320*mm* face width. The rolling speed was set at 34*rpm*. A box type furnace with the maximum working temperature of 1400 °*C* was employed to heat up the specimens to the desired rolling temperature. The experimental procedure for this two-pass rolling sequence is described in detail in Ref. [14].

In Fig. 5, the predicted exit cross sections are compared with experimentally measured ones. Small differences are noted. This difference could be caused by error in roll gap setting. In overall, the cross sectional shapes predicted by FE simulation are in good agreement with those measured.

In round-oval pass rolling, normal pressure has a maximum value at initial contact point. However, in the case of oval- round pass, normal pressure has a maximum value at between contact edge and exit section to the spread direction. It is deduced that maximum wear

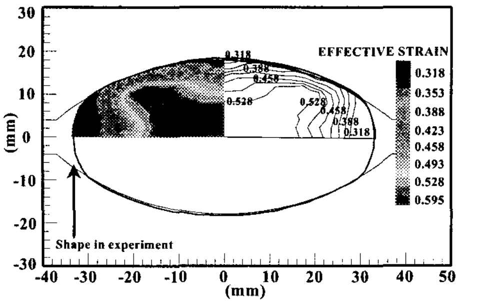

Fig. 5(a) The shape of exit from FE-analysis compared with experimental results in round-oval pass

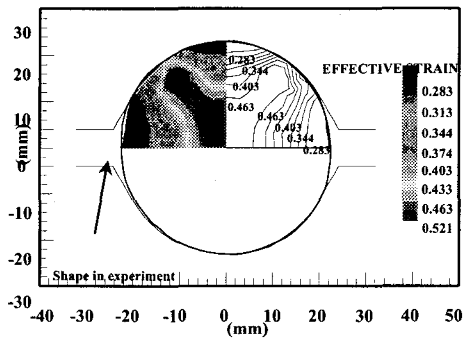

Fig. 5(b) The shape of exit from FE-analysis compared with experimental results in oval-round pass

might be occurs at the middle part of roll groove for the round-oval pass and at the roll shoulder part for the oval-round pass.

The temperature at roll surface increases up to 400~420 $^{\circ}C$ at steady state and workpiece temperature reached 650~670 $^{\circ}C$ after contact time, 0.1 sec, passed. In this study, the roll surface temperature is calculated based on a single revolution of the roll assuming heat transfer from the roll to the surroundings as normal temperature (20 $^{\circ}C$). To account for roll wear exactly, one has to consider that roll surface temperature according to revolutions is subjected to heat transfer from the roll to the surroundings. There are some inexplicable things in this study and we must think it over again with experimental results. This paper deals only the effects of transformation of work of deformation into heat considering thermal softening depending upon rolling time and temperature in working conditions. Whole results are summarized in Table 3.

Table 3 The results of FE-simulations

Results	*1st pass*	*2nd pass*
	Round-oval	*Oval-round*
Section area (mm²)	*2076*	*1658*
Contact area (mm²)	*2300*	*1260*
Wide spread (mm)	*68.2*	*42.6*
Area reduction (%)	*39.2*	*20.0*
Max slip ratio (%)	*4.35*	*1.77*
Average slip ratio (%)	*1.93*	*1.77*
Load (kN)	*162*	*87.5*
Contact time (sec)	*0.1348*	*0.112*
Max. roll temp. (℃)	*440*	*442*
Min. rod temp. (℃)	*675*	*673*

4. Wear analysis for DCI roll

4.1 Wear analysis

A wear model is proposed based on Archard's wear model [2] which is function of normal pressure, sliding length, and hardness of roll for predicting the variations of wear profile of the roll during hot rod rolling. If hardness of roll changes according to temperature and contact time between roll and material, Archard's wear model can be rewritten and the wear depth, $\delta w_{t+\Delta t}$, at time $t+\Delta t$, can be calculated by Eq.(3).

$$\delta w_{t+\Delta t} = \delta w_t + \frac{k}{H_v(T,t)}[\sigma_n \Delta v]_{t+\Delta t} \Delta t \quad on \ \partial\Omega^{Tool} \qquad (3)$$

where, σ_n is the normal stress contacting of the roll surface, Δv is the sliding velocity between the roll and workpiece, k is a wear coefficient, T is temperature and t is contact time. The sliding velocity and the normal stress on the discretized roll surface $\partial\Omega^{tool}$, can be achieved by FE-simulation. In order to predict the roll wear, the wear depth of roll is calculated at each deformation step on contact area using the results of FE-simulation. To describe better the deformation behavior between roll and workpiece interface, contact-searching algorithm was suggested in previous work [15].

4.2 Wear profile

Fig. 6 shows non-uniform relative velocity distribution of workpiece for the round-oval and oval-round passes rolling. For both oval-round pass and round-oval pass, backward slip is much larger than forward slip and backward slip give rise to abrasive wear of roll. The wear model expressed as a function of relative

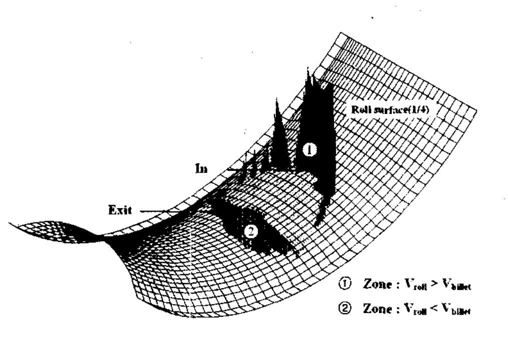

Fig. 6(a) Profile of relative velocity in contact area in oval-round pass

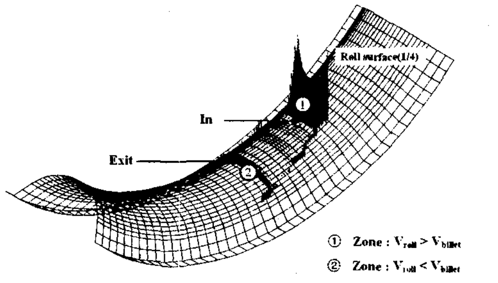

Fig. 6(b) Profile of relative velocity in contact area in round-oval pass

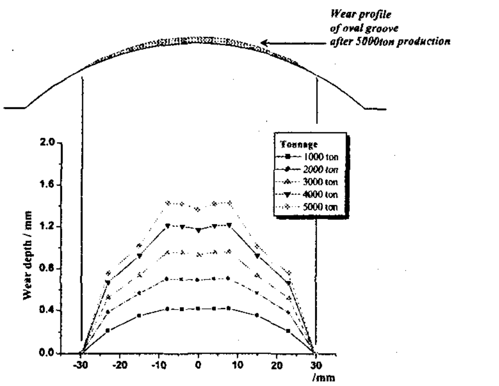

Fig. 7(a) Wear profile after 5000ton production for DCI Roll in oval-round pass

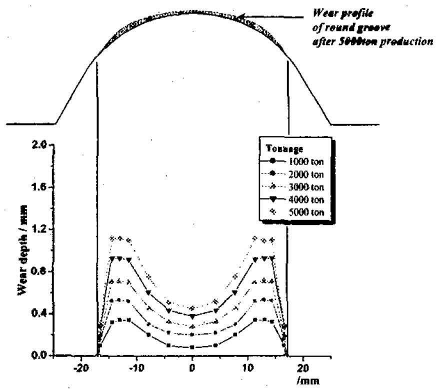

Fig. 7(b) Wear profile after 5000ton production for DCI Roll in round-oval pass

velocity, temperature and pressure at each time step is coupled with three-dimensional finite element analysis.

The wear profile is predicted at every 1000*ton* production and newly generated roll groove shape becomes input to FE analysis for next prediction of the wear profile. The terminology 'Production (or tonnage)' means a yield of steel. After production of a specific amount of rolled steel, the wear profile of the roll groove is obtained. In this study, after five repetitions, i.e., 5000*ton* production, the wear profile of roll groove is plotted.

Fig. 7 shows the wear profile along with each production stage for DCI roll for the two-pass rolling sequence (Fig. 4). For round-oval pass, the wear profile follows the second order parabolic curve at 1000*ton* and 2000*ton* production. It is interesting to note that the wear profile becomes skewed as tonnage increases. At 4000*ton* production, local wear at the beyond the center of roll groove starts to increase. We can see that local wear increase as the production rises. Therefore, inappropriate deformation flow due to local wear might force to exert additional localized pressure and wear on the groove walls.

4.3 Adjustment of roll gap using ANN

To keep uniform exit cross-sectional area during rolling, roll gap (pass height) have to be adjusted at each pass with due consideration of roll wear. So, in this paper, the technique using ANN has been proposed to keep the cross-sectional area during rolling constant [16~18]. Fig. 8 shows the variation of a quarter cross-sectional area according to tonnage due to roll wear.

In order to predict the roll gap size, the *y2* and a quarter cross-sectional areas as shown in Fig. 8 are considered as design parameters and corresponding maximum wear depth as teacher signals. The input data for training of neural network and the outputs are shown in Table 4.

The trained network has been tested with the *y2* for each production (per 1000ton) and the initial a quarter

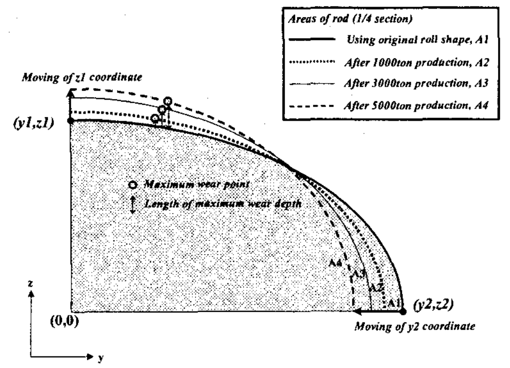

Fig. 8 Variation of area according to roll wear

Table 4 The predicted results by ANN

Rolling process			Input data for ANN: Input layer: y2 (mm)	Input data for ANN: Input layer: 1/4section area (mm^2)	Input data for ANN: Output layer: Wear depth (mm)	Prediction: Output: Wear depth for adjustment (mm)
R-O	Training data	Initial	34.10	519.1500	0	0.0001
		1000ton	33.94	524.2440	0.418	0.4182
		2000ton	33.78	528.3563	0.704	0.7039
		3000ton	33.60	533.5922	0.961	0.9615
		4000ton	33.42	536.4855	1.215	1.2146
		5000ton	33.25	539.9810	1.430	1.4298
	Test data	1000ton	33.94	519.1500	-	0.1555
		2000ton	33.78	519.1500	-	0.3359
		3000ton	33.60	519.1500	-	0.5361
		4000ton	33.42	519.1500	-	0.7163
		5000ton	33.25	519.1500	-	0.8829
O-R	Training data	Initial	21.30	414.5100	0	0.0007
		1000ton	21.12	418.2443	0.344	0.3435
		2000ton	20.98	421.7150	0.533	0.5323
		3000ton	20.75	425.3511	0.709	0.7102
		4000ton	20.49	429.1050	0.925	0.9260
		5000ton	20.30	433.2213	1.115	1.1148
	Test data	1000ton	21.12	414.5100	-	0.1573
		2000ton	20.98	414.5100	-	0.2776
		3000ton	20.75	414.5100	-	0.4414
		4000ton	20.49	414.5100	-	0.5775
		5000ton	20.30	414.5100	-	0.6617

*R-O: Round-oval pass, O-R: Oval-round pass

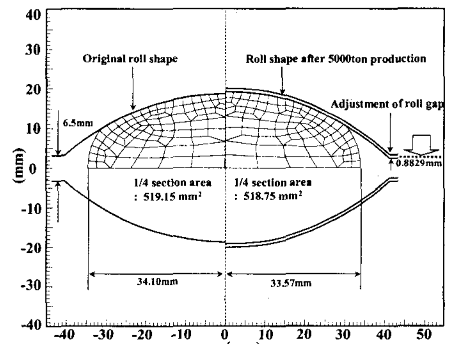

Fig. 9(a) Adjustment of roll gap for uniform cross-sectional area using ANN in oval-round pass

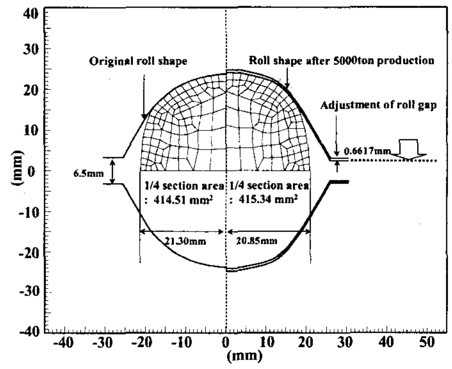

Fig. 9(b) Adjustment of roll gap for uniform cross-sectional area using ANN in round-oval pass

cross-sectional area (oval: 519.15 mm^2, round: 414.51 mm^2) to predict the pass height that maintains an even cross-sectional area constant according to tonnage (production).

The predicted results show that the roll gap has to be reduced 0.8829*mm* and 0.6618*mm* in round-oval and oval-round passes respectively after 5000ton production. So, in order to verify the predicted results of ANN, FE-simulations have been carried out using the adjusted roll gap. As shown in Fig. 9 a quarter cross-sectional areas after 5000ton production are concordant with the initial areas for each pass.

5. Conclusion

In this paper, the technique using ANN has been proposed to keep uniform exit cross-sectional area during hot-rod rolling process considering roll wear, To predict the wear profile of DCI roll for round-oval and oval-round passes in hot rolling process, a modified Archard's wear model has been proposed with consideration of the thermal softening of DCI roll. Then, wear depth of roll was calculated at each deformation step on contact area using the results of FE-simulation. The presented study demonstrated that the proposed wear model could be used effectively in quantitative prediction of the roll wear profile for the oval and round pass rolling. Also, it has been found that the use of ANN has got the immediate results to maintain uniform cross-sectional area constant during rod (or bar) rolling process. These results might be used as a guideline to adjust roll gap in the rod (or bar) mill and would be extended further study to determine roll life.

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