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Experimental study for roll gap adjustment due to roll wear in single-stand rolling and multi-stand rolling test

S. M. Byon[1], H. S. Park[1] and Y. Lee[2,*]

[1]Department of Mechanical Engineering, Dong-A University, Busan, 604-714, Korea
[2]Department of Mechanical Engineering, Chung-Ang University, Seoul, 156-756, Korea

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Abstract

To investigate a correlation between the amount of wear and roll gap (pass height) adjustment, we performed a single-stand reversible pilot groove rolling test as well as rolling test in an actual rod mill. In case of the pilot rolling test, we designed wear contour (profile) and machined it on the original roll groove (i.e., roll groove with no wear) to make the roll groove worn down. For the actual rod mill test, we developed a measuring device which can detect the actual wear profile.

To determine the amount of roll gap adjustment, we propose a model for equivalent roll gap decrement which reduces the increased exit cross sectional area due to wear. We applied the proposed model to multi-stand rolling (roughing train of POSCO No. 2 Rod Mill) as well as single-stand reversible rolling. The wear profile of rolls worn down at each stand in mill yard was measured at different roll tonnage.

The pilot hot rolling test shows that variation of exit cross sectional area is almost linearly proportional to roll gap change while the roll gap decreases from reference roll gap (6.5mm) to 3.5mm. In an actual rod mill which has consecutive rolling system, relationship between tonnage (total amount of tons that the produced rod weighs) and roll gap change at a stand is dependent on the rolling type (oval-to-round or round-to-oval) together with the cross sectional shape of incoming workpiece.

Keywords: Roll gap adjustment; Equivalent roll gap; Roll wear; Roll groove design; Rod rolling

1. Introduction

Rods (or bars) are generally produced using rolls on which various groove are arranged. Initially heated billet is deformed into rod (or bar) as they pass through multiple sets of grooved rolls. Equipment that set of grooved rolls is installed is called 'stand'. Exit cross sectional area of workpiece at each stand is progressively reduced until the desired cross sectional shape is achieved at the last stand.

Recently, high quality of rod products is in great demand and mill engineers together with researchers in rod rolling process are making efforts to improve the quality of rod products. There are several factors which determine the quality of rod products. Among them, a precise shape of final products is one of very important factors. In rod rolling process, final products are supposed to have a perfect round cross section but, in reality, cross section with a perfect roundness does not exist. This is what we call 'ovality', which is defined as target diameter subtracted by the length of short axis or that of long axis of the cross section. In rod mill, ovality is usually in the range of 0-±0.15mm.

The biggest obstacle for us to have zero ovality is the wear on roll. However, we cannot avoid the roll wear in rolling process which uses frictional force for rolling itself. Roll wear occurs continuously during rolling and the amount of roll wear increases as roll

*Corresponding author. Tel.: +82 2 820 5256, Fax.: +82 2 814 9476
E-mail address: ysl@cau.ac.kr
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tonnage does. (Terminology 'roll tonnage' implies the total number of tons that the produced rod weighs.) To deal with the wear problem in rolling process, one has to know wear profile (contour) of roll and figure out the effect of wear on the variation of exit cross sectional area. The ECSA (Exit Cross Sectional Area) can be controlled with adjusting the roll gap (pass height) of the groove rolls at each stand and the amount of the roll gap adjustment has been relied mainly on skillful operator's experience on roll wear. In this respect, the shape of final products becomes inferior ultimately if the operator's experience on exit cross sectional shape is not right. Hence, a study of roll gap adjustment has been highly desirable to deal with the shape quality problem of final products.

Kim et al. [1] calculated the wear contour of work roll for a pilot rod rolling mill with two passes (oval and round roll groove) using finite element method coupled with Archard wear model [2]. They reformulated Archard's wear equation as an incremental form and the hardness of the roll was expressed as a function of rolling time. The roll wear profile was calculated at each deformation step in consideration of relative sliding speed and normal roll pressure at contact area. Recently, Byon and Lee [3] presented a semi-analytical model which can predict the wear contour in oval-to-round (or round-to-oval) groove rolling. They assumed that the wear contour could be expressed as a second order polynomial function, which can be obtained by a linear interpolation of the radius of curvature of grooved roll and incoming workpiece (material) geometry together with a weighting function. These studies [1, 3], however, were confined to measuring and predicting roll wear contour (profile) only. In addition, no study of roll gap adjustment in an actual rod mill has been reported as yet.

In this study, we carry out a single-stand reversible pilot rolling test with roll groove (oval and round shape) worn down as well as roll groove with no wear. It should be noted that measuring wear in pilot rolling mill is almost impossible since at least a few hundred tons of material should be rolled in order for the wear profile to be detected clearly. Hence, we designed wear contour based on wear contour on roll groove proposed by Kim et al [1] and machined it on the original roll groove (roll groove with no wear) to acquire the roll groove worn down. To determine the roll gap (pass height) adjustment we introduced the concept of equivalent roll gap decrement which reduces the increased exit cross sectional area due to wear. We applied the concept to the single-stand reversible pilot rolling process and the roughing train of POSCO No. 2 Rod Mill which has the multi-stand continuous rolling sequence. The wear profile of rolls worn down at the six stands was measured at different roll tonnage using a roll wear contour reader developed by Byon [4]

2. Background for roll gap adjustment

Fig. 1 shows the schematic of cross sectional shape change of workpiece (material) during round-to-oval groove rolling. The round-to-oval groove rolling implies that workpiece with a round cross section is rolled in oval-shaped roll groove and subsequently workpiece with an oval cross section is rolled out. For convenience, the oval-shaped roll groove is referred as oval roll groove and round-oval groove rolling hereafter. The oval-to-round groove rolling is vice versa. Section A-A, B-B and C-C, respectively, corresponds to the position where cross section of the workpiece is about to be rolled, being deformed and leaving the oval roll groove.

We know that wear occurs at the region where the oval roll grooves and workpiece are fully in contact

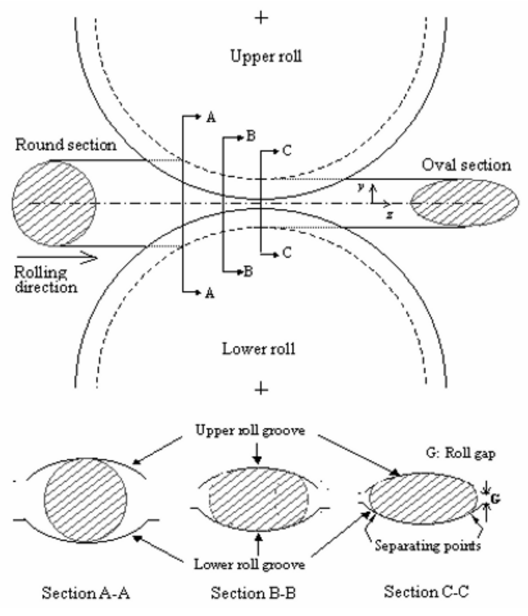
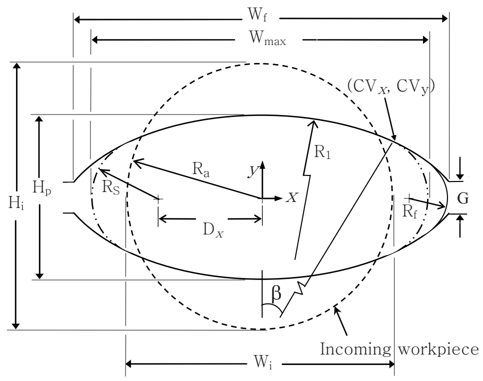
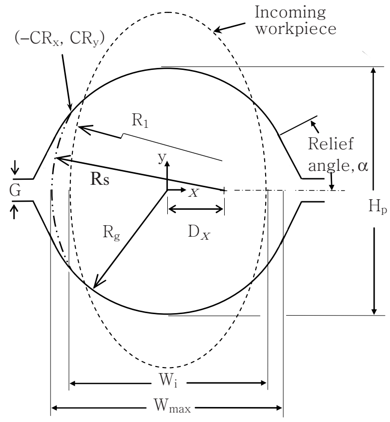


Fig. 1. Schematic of cross sectional shape change during the round - oval pass rolling. The separating points indicate the point that the roll grooves stop contacting the workpiece at the exit of rolling.

Table 1. Equations for the separating points in round-oval and oval-round groove rolling sequence [5, 6].

Rolling sequence	Separating points x coordinate / y coordinate	Geometric designations
Round-oval	$CV_x = R_1 \sin\beta$ $CV_y = R_1 \cos\beta$ $\beta =$ $\cos^{-1}\left(\dfrac{R_1 - H_p/2}{R_1 - R_s}\right)$	
Oval-round	$CR_x =$ $\dfrac{-\left[\dfrac{H_p^2 - W_{max}^2}{4} - D_x W_{max}\right]}{2D_x}$ $CR_y = \left[\left(\dfrac{H_p}{2}\right)^2 - CR_x^2\right]^{\frac{1}{2}}$	

Note: R_s is the radius of curvature of the surface profile and R_f represents the radius to be achieved when the maximum spread of the exit cross section of workpiece (W_{max}) is equal to the width of the roll groove area (W_f).

each other at the section C-C. Hence, we must determine the separating points that the roll groove stops contacting the workpiece at the exit position, i.e., section C-C. We can easily compute the separating points once we know the stress free surface profile of workpiece at the exit position, i.e., section C-C. The stress free surface profile indicates the line contour of workpiece which does not contact the roll groove at the exit. The stress free surface profile is referred as the surface profile after this. The separating point and surface profile for the round-oval groove rolling and oval-round groove rolling is summarized in Table 1. Details for the equations are described in Refs. [5, 6].

Fig. 2 illustrates the concept of equivalent roll gap decrement, ΔG in oval groove. Configuration of lower roll groove is omitted for brevity. Equivalent

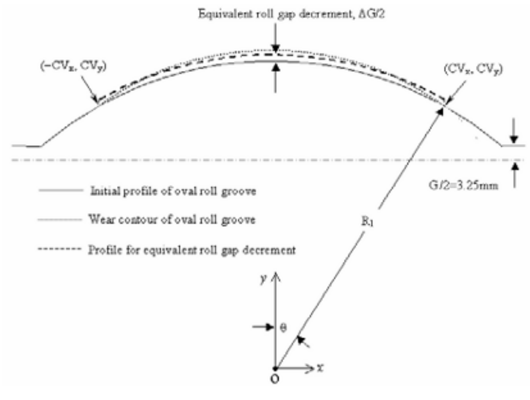


Fig. 2. Concept for equivalent roll gap decrement, ΔG.

roll gap decrement implies the amount of pass height

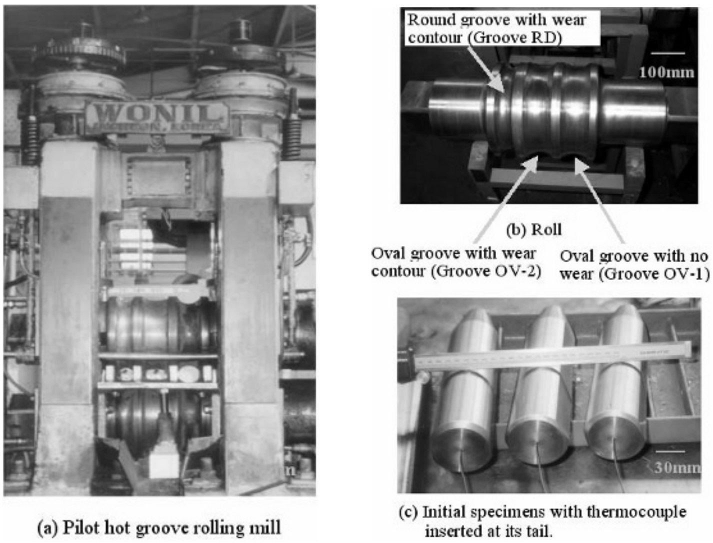


Fig. 3. (a) General view of pilot hot groove rolling mill, (b) roll with one round groove and two oval grooves and (c) initial specimens with diameter of 60mm used in the rolling test.

(roll gap) that has to be reduced when wear occurs. It is constant along the profile of equivalent roll gap. The method to determine the equivalent roll gap decrement is as follows.

First, we calculate wear area A_{wear}, the inside area surrounded by initial profile (contour) of oval roll groove and wear contour of oval roll groove (marked in dotted line) in the following

$$A_{wear} = \int_{-CV_x}^{CV_x} f_w(x) \ dx - \int_{-CV_x}^{CV_x} f_o(x) \ dx . \quad (1)$$

$f_w(x)$ and $f_o(x)$ stand for a function of wear contour and that of original oval groove shape, respectively. One can use PRO-E® to calculate the wear area as well.

Second, the equivalent roll wear area, marked in dashed line, is expressed as a curved rectangle and is calculated using Eq. (2)

$$A_{eq} = 2\theta \ R_1 \ \Delta G \text{, where } \theta = \sin^{-1} \frac{CV_x}{R_1} . \quad (2)$$

Finally, putting the equivalent wear area A_{eq} equal to the wear area A_{wear} yields the equivalent roll gap decrement, ΔG. The equivalent roll gap decrement for round groove is also calculated in a similar manner.

3. Wear contour

3.1 Single-stand reversible rolling

It is worth noting that having wear on roll in pilot rolling mill is almost impossible since at least a few hundred tons of material should be rolled in order for the wear profile to be detected clearly. Hence we designed roll wear contour based on the finite element analysis results [1]. The round and oval roll groove which have wear contour are machined with NC lathe.

Fig. 3(a) shows a single-stand two-high laboratory mill driven by 75kW constant torque, DC motor. DCI (Ductile Casting Iron) rolls were used, with 310mm diameter and 320mm face width. The roll speed was set at about 0.5m/s (34rpm). A box type furnace with the maximum working temperature of 1400°C was employed to heat up the specimens to the desired rolling temperature. Fig. 3(b) and (c) show the roll with a round groove, two oval grooves and initial specimens with diameter of 60mm used in the rolling test.

Fig. 4 shows the geometrical designation of initial roll groove and wear contour for oval groove in pilot mill. Upper roll groove is depicted for expediency. All units are in millimeter. The radius of curvature of initial oval roll groove is R_1 and half pass height ($H_p/2$) is 18.75mm. Separating point ($-CV_x$, CV_y) is (-31.30mm, 51.78mm) and the radius of curvature (R_0) of oval roll groove worn down is 53.48mm. Maximum wear at the center of roll groove is 1.39mm.

Fig. 5 illustrates the geometrical designation of initial roll groove and wear contour for round roll groove in pilot mill. In case of round groove, wear

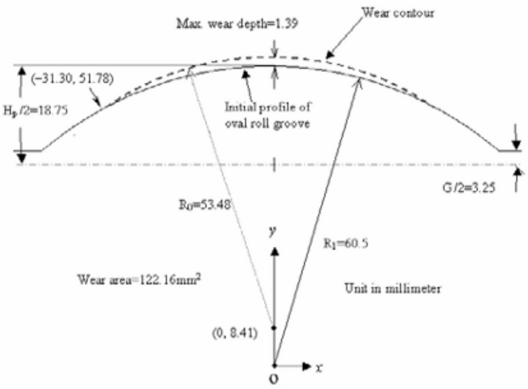


Fig. 4. Geometrical designation for initial roll groove and wear contour of oval groove in pilot rolling mill.

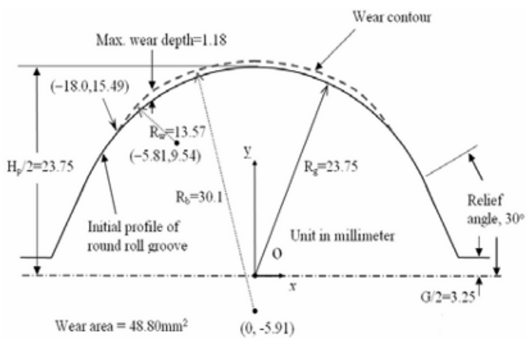


Fig. 5. Geometrical designation for initial roll groove and wear contour of round groove in pilot rolling mill.

contour have two radius of curvature, R_b and R_w. The starting point of R_b is on y-axis but that of R_w is neither on the x-axis nor y-axis. Maximum wear occurs at the region what is called 'roll shoulder' which is located between center of roll groove and separating point. Note that, in case of oval groove, maximum wear occurs at the center of roll groove. This is because the effect of grinding between roll and workpiece on wear is most significant at the roll shoulder region.

3.2 Multi-stand continuous rolling

Single-stand rolling test has a strong point such that one can easily measure the exit cross sectional shape of workpiece at a given groove after rolling while roll gap is reduced. Hence, we could express the variations of exit cross sectional area as a function of roll gap adjustment when a certain amount of wear, i.e., wear contour (profile) on work roll already exists. But, in multi-stand continuous rolling sequence such as an actual rod mill or bar mill, operators want to have information, a relationship between the roll gap adjustment and roll tonnage since roll wear contour is continuously changing. If we want the wear contour to be variable, one has to make wear contour by machining it many times and perform rolling test. This requires high expense and is almost impossible.

Thus, to obtain a relationship between the roll gap adjustment and roll tonnage, one has to rely on the multi-stand continuous rolling test to take wear contour (profile) as a parameter. However, TU Bergakademie Freiberg, Germany is the only scientific institute in the world with four stands of continuous rod (or bar) rolling mill. This was built in 1982 after industrial requirements for a special equipped laboratory mill to realize practice relevant rolling tests and other investigations [7]. Even this four-stand continuous rod (or bar) rolling mill can not simulate the roll wear and roll gap adjustment in terms of roll tonnage because we can not roll hundred tons of workpiece. Note the diameter and length of initial specimen for the four stands of continuous rod (or bar) rolling mill is 15mm and 1000mm, respectively.

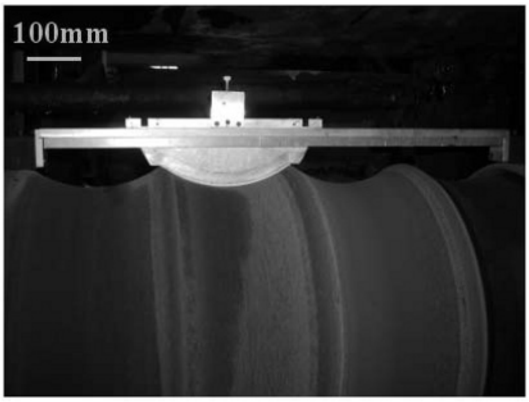
4. Experiment

4.1 Single-stand reversible pilot rolling test

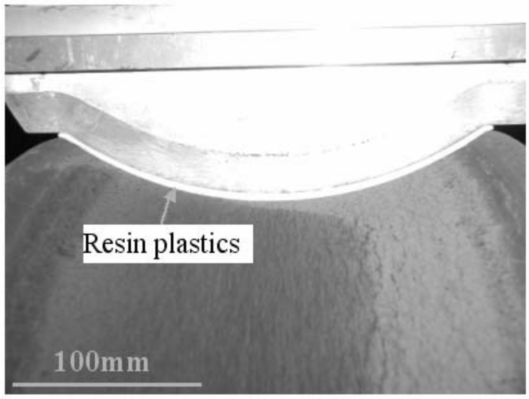
The initial specimen was rolled in the oval roll groove at about 1000°C without lubrication. To measure the rolling temperature of the workpiece (specimen), K-type thermocouple was embedded in 40mm deep holes drilled in the tail ends of the specimen as shown in Fig. 3(c).

Eight initial specimens in total were used. The four initial specimens were rolled directly in the oval roll groove worn down (Groove OV-2 in Fig. 3(b)) as roll gap was reduced from 6.5 to 5.5, 4.5 and 3.5mm. To make initial specimen for the round groove with wear (Groove RD in Fig. 3(b)), we rolled the four initial specimens left in the oval groove with no wear (Groove OV-1 in Fig. 3(b)). This rolling leads us to have four workpieces with oval cross sectional shape and subsequently these workpieces were used as initial specimens for round groove worn down while roll gap is reduced from 6.5 to 5.5, 4.5 and 3.5mm. The workpiece with the oval shape was then rolled into the round groove after it was rotated 90 degree about its length direction. Entry guides were installed in front of the round roll groove to minimize sideway

(a) Actual continuous rod rolling mill

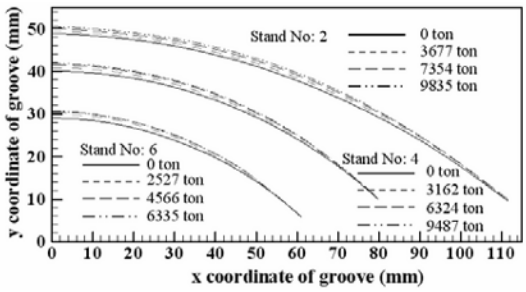


(b) Wear contour reader mounted on oval roll groove

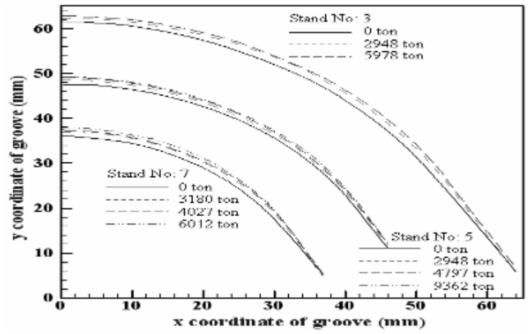


(c) Resin plastics filled into region worn down

Fig. 6. (a) General view of continuous rod rolling mill, (b) Measurement of roll wear for oval groove and (c) The region worn down at a oval roll groove is being copied.



(a) Oval roll groove



(b) Round roll groove

Fig. 7. Roll wear profile in terms of roll tonnage at roughing train of POSCO No. 2 Rod Mill.

bending of specimen.

4.2 Multi-stand continuous rolling test

The roll wear contour reader [4] was applied to POSCO No. 2 Rod Mill which has a feature of the horizontal-vertical type tandem rolling with oval-round (or round-oval) pass sequence, except pass No. 1 (box pass). The wear contour at each stand was measured at a specific roll tonnage. Fig. 6(a) and (b) illustrate the roughing trains in actual rod mill and the wear contour reader mounted on oval roll groove. Fig. 6(c) is magnification of Fig. 6(b) along roll groove. Basic idea adapted in this equipment is using 'resin plastics' which can flow without restraint into any region worn down under small external load. We can then know the wear contour of grooved roll by measuring the deformed shape of resin plastics.

Fig. 7 illustrates roll wear profile in terms of roll tonnage at different stand number of the roughing train. The quarter of wear contours is shown due to their symmetric configuration. It shows wear profile at each stand is enlarged as the roll tonnage increases. Wear measurement was not performed for box roll groove at the stand No. 1 since wear at the box roll groove is very small compared with the others. Note that roll property of the box roll groove is 'Adamite' and that of the others (oval and round groove) is 'DCI' (Ductile Casting Iron).

5. Results and discussion

5.1 Single-stand reversible pilot rolling test

Single-stand rolling test gives a relationship between roll gap (pass height) and ECSA (exit cross sectional area) under a pre-determined wear contour. Fig. 8 shows correlation between roll gap (pass height) and ECSA for the given roll wear contour as shown in Fig. 4. The exit cross sectional shape (a white colored-oval shape on a black ground) and measured area at each roll gap also appears inside of the Fig. 8.

In the reference roll gap (initially designed roll gap, i.e., 6.5mm) and oval groove with no wear, ECSA is 2060mm^2 (marked in empty triangle). In the reference roll gap, however, when the initial specimen with round section was rolled in the oval groove worn down, ECSA increased to 2150mm^2 (marked in empty rectangle at 6.5mm). Hence we decreased the roll gap, i.e., pass height, to make ECSA equal 2060mm^2 approximately. We could observe that ECSA decreases as the roll gap decreases from 6.5mm to 5.5, 4.5 and 3.5mm.

Applying least square method to these data yields ECSA equation for the oval groove, A_{oval} in terms of roll gap (solid line in Fig. 8). We can calculate ΔG (1.86mm) from Eq. (2). Subtracting this ΔG from the reference roll gap (6.5mm) yields the amount of roll gap, 4.64mm (=6.5mm-1.86mm). We can then obtain a corrected ECSA, 2054mm^2 by substituting this value (4.64mm) to the equation, A_{oval}. When the reference and corrected ECSA are compared, difference is 0.29%.

Fig. 9 illustrates the measured ECSA (marked in empty rectangle) as well as the exit cross sectional shape when roll gap is reduced from 6.5mm to 5.5, 4.5 and 3.5mm in round groove rolling. Symbol with empty triangle designates reference ECSA (1628 mm^2) when the specimen with oval cross section is rolled in the round groove with no wear. Unlike the oval groove rolling, rise and fall of ECSA along the roll gap decrement is somewhat high. The decrement of ECSA in the round groove rolling has some fluctuations at roll gap of 5.5mm, compared with that in the oval groove rolling. But it is assumed that linear equation fitting these data is good enough to calculate the amount of roll gap decrement. Hence, the least square method was applied to these data and ECSA equation for the round groove, A_{round} in terms of roll gap, G was obtained.

Symbol with solid circle represents the corrected roll gap to reach the reference ECSA when the specimen with oval cross section is rolled in the round groove worn down. This corrected roll gap (5.28mm) is obtained from the roll gap adjustment model, Eq. (2). Plugging this corrected roll gap in the equation,

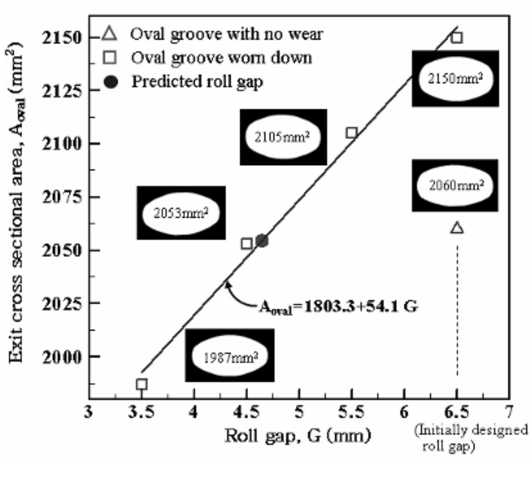


Fig. 8. Measured exit cross sectional area (ECSA) as a function of roll gap in oval groove in pilot rolling.

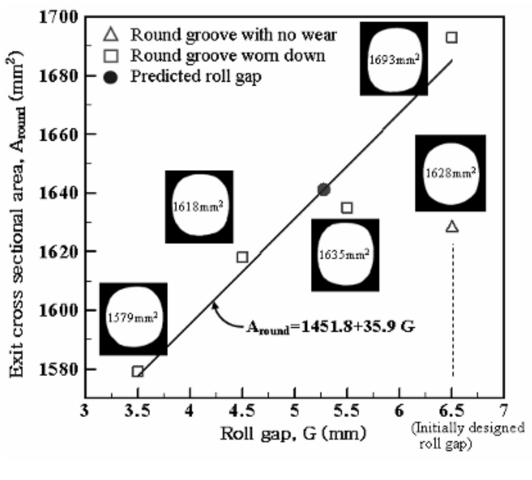


Fig. 9. Measured exit cross sectional area (ECSA) as a function of roll gap in round groove in pilot rolling.

A_{round} gives a corrected ECSA, 1641mm^2. When the reference ECSA is compared to the corrected one, difference is 0.80%. The difference, 0.29% for round-to-oval groove rolling and 0.80% for oval-to-round groove rolling is acceptable to be applicable to roughing stands in actual rod mill since mass unbalance between stands is controlled by LTC (Lower Tension Controller) system up to 2.0%.

5.2 Multi-stand continuous rolling test

Table 2 shows the amount of roll gap adjustment as a function of roll tonnage for six stands at the roughing train of POSCO No. 2 Rod Mill. Amount of wear increased is calculated by subtracting the original roll groove area with no wear from the roll groove area with wear. Amount of roll gap decrement (i.e., equivalent roll gap adjustment; ΔG) at each stand at different tonnage is calculated by Eq. (2). As tonnage increases, the amount of ΔG increases.

To describe the equivalent roll gap adjustment (ΔG) in terms of roll tonnage, some manipulations should be performed. Since the physical quantity, 'tonnage' has unit of 10^3 while roll gap adjustment unit of 10^{-1}, we may need to non-dimensionalize these to obtain a relationship between them. Hence, we define non-dimensional tonnage and roll gap adjustment as follows.

$$T^* = \frac{T}{T_{max}} \quad (0 \le T^* \le 1) \tag{3}$$

$$\Delta G^* = \frac{\Delta G}{G} \quad (0 \le \Delta G^* \le 1) \tag{4}$$

T_{max} represents the maximum roll tonnage and G stands for the reference roll gap.

Fig. 10 illustrates the non-dimensional roll gap adjustment ΔG* as a function of non-dimensional tonnage T* at the stands with oval roll groove (i.e., Stand no. 2, 4 and 6). In these stands, the amount of roll gap adjustment increases linearly as roll tonnage does and the non-dimensional roll gap adjustment ΔG* can be expressed as a linear function of non-dimensional tonnage T*. This indicates that even though wear occurs continuously as a function of roll tonnage we can keep the exit cross sectional area (ECSA) constant initially designed in roll pass schedule if we use the T* and ΔG* relation (linearly regressed equation) inside of Fig. 10. In other words, at a specific roll tonnage, we can keep the mass balance constant at each stand using the equivalent roll gap adjustment proposed in this study. The mass balance means the equilibrium of material flow rate between stands whose dimension is [m^3/sec] and calculated by multiplication of the exit cross sectional area and the outgoing speed of material at the exit cross section at a stand.

Fig. 11 illustrates the non-dimensional roll gap adjustment, ΔG* as a function of the non-dimensional roll tonnage, T* at the stands with round roll groove (i.e., Stand no. 3, 5 and 7). In contrast to oval roll groove, however, the relationship between non-dimensional roll gap adjustment ΔG* and non-dimensional tonnage T*is not linear. The relation is of a second order polynomial form. As roll tonnage approaches the maximum roll tonnage, the amount of roll gap adjustment saturates and decreases somehow. This might be attributed that, in case of oval roll groove, the radius of curvature is very large compared with that of round roll groove. Hence wear contour in oval roll groove is smooth along roll groove as roll tonnage increases. However, wear contour in round roll groove is concentrated locally as roll tonnage increases. This might leads to retardation of wear in round roll groove and therefore we can observe that

Table 2. Equivalent roll gap adjustment (ΔG) in terms of increment of roll tonnage Unit of tonnage is [ton] and roll gap adjustment is [mm].

Std. No. 2 (Oval groove)	*Tonnage*	3677	7354	9835	Max. tonnage: 11,000
	ΔG	1.2833	2.4233	3.2855	Ref. roll gap: 21
Std. No. 3 (Round groove)	*Tonnage*	2948	5978	9451	Max. tonnage: 9,600
	ΔG	2.7040	3.5990	3.6729	Ref. roll gap: 13
Std. No. 4 (Oval groove)	*Tonnage*	3162	6324	9487	Max. tonnage: 9,600
	ΔG	1.4892	2.6083	3.1399	Ref. roll gap: 18
Std. No. 5 (Round groove)	*Tonnage*	2948	4797	9362	Max. tonnage: 9,600
	ΔG	1.9720	2.9555	3.2045	Ref. roll gap: 12
Std. No. 6 (Oval groove)	*Tonnage*	2527	4566	6335	Max. tonnage: 6,400
	ΔG	1.5819	2.4045	2.4490	Ref. roll gap: 11
Std. No. 7 (Round groove)	*Tonnage*	3180	4027	6012	Max. tonnage: 6,400
	ΔG	2.3229	3.0114	3.9636	Ref. roll gap: 7

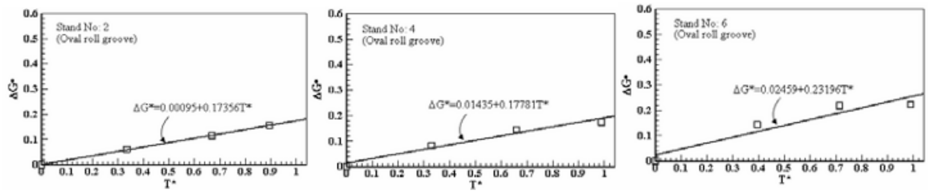


Fig. 10. Non-dimensional roll gap adjustment(ΔG*) as a function of non-dimensional roll tonnage(T*) at the stands with oval roll groove (Stand No. 2, 4 and 6)

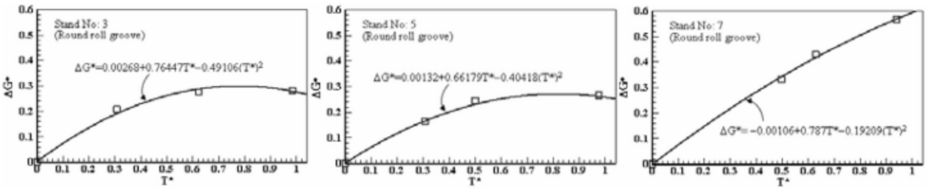


Fig. 11. Non-dimensional roll gap adjustment(ΔG*) as a function of non-dimensional roll tonnage(T*) at the stands with round roll groove (Stand No. 3, 5 and 7).

amount of roll gap adjustment saturates at certain amount of tonnage.

6. Concluding remarks

To understand better wear in groove rolling process, we performed a single-stand reversible pilot (oval and round shape) rolling test with roll groove worn down as well as roll groove with no wear. We carried out multi-stand rolling test at roughing train in POSCO No. 2 Rod Mill as well and then measured wear profile in terms of roll tonnage. We suggested a model for equivalent roll gap decrement which reduces the exit cross sectional area increased due to wear and applied the proposed model to these rolling tests.

1) The variation of exit cross sectional area is almost linearly proportional to roll gap change while the roll gap decreases from reference roll gap (6.5mm) to 3.5mm in the pilot hot rolling test. This indicates that we can maintain mass balance by adjusting roll gap (pass height) in oval-round (or round-oval) pass rolling sequence.

2) In an actual rolling process which has continuous wear during rolling, the variation of ECSA (exit cross sectional area) at each stand can also be kept constant through roll gap (pass height) adjustment once we have a proper equation which relates roll gap adjustment and tonnage. In oval roll groove, the relationship between roll gap adjustment and tonnage is a linear form, but for round roll groove it has a second order polynomial form.

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