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Study of Friction and Rollers Wear in Hot Strip Mill of Mobarakeh Steel Company

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ABSTRACT: One of the main factors affecting the production of a uniform sheet profile in hot strip milling process is the amount of friction in strip rolls. The roll friction is considered as one of the complex phenomena in hot strip mill process. In this article, we intend to obtain a mathematical model to calculate friction profile of rollers of Mobarakeh steel company hot strip mill unit. To do this, we need to prepare efficient models to calculate force, friction and wear; Sims and Oike models will be used accordingly. As the simulation and experimental results show, there is a good conformity between the results.

Keywords: Wear, Friction, Milling rolls, Hot strip mill unit, Mobarakeh Steel Company

I. INTRODUCTION

Today, two important aspects of quality production of hot rolled slabs, thickness uniformity in slab width profile and slab flatness are center of attentions. The necessity of thickness non-uniformity reduction in slab width and flatness increment is usually due to consumers' demands for more accurate dimensions which is consequence of necessity of modern production processes [1-4]. Moreover, according to new standards, slabs are sold based on their dimensions, length, width, and thickness which have their own tolerances which results in the necessity of controlling slab thickness [5-7]. One of the influential factors on slab profile flatness is the amount of wear in milling rolls. Wear is one of the factors contributing in roll erosion which changes the shape of rolls and consequently the shape of the products. This phenomenon not only has undesirable quality effects on hot rolled products, but decreases the capability and functionality of milling process. Since shape and surface of milling rolls get eroded due to wear, the possibility of crack formation on the surface of the rolls goes up and continuing production process could result in crack propagation and cause serious damages to rolls. Since a whole lot of factors are contributing, directly or indirectly, to roll wear in hot strip mill process, this phenomenon is considered as a complicated one in hot strip mill process. Some researchers are performed in order to draw a better understanding of wear phenomenon, such as measuring and categorizing different types of process and wear mechanism in milling rolls. There are a lot of wear mechanism contributing in milling rolls such as adhesion wear, scratching wear, fatigue wear, and chemical wear.

Today, steel slab production companies use advanced control methods to control quality and dimensions of products, examples of which are automatic thickness control system, automatic width control system, and slab shape and profile control system. In these systems, in order to control desired parameter, advanced mathematical models are implemented to calculate necessary settings for control systems of milling process. Displacement mechanism of active rolls is used to control their wear profile. Moving rolls during rolling process, this system distributes wear along mill length which prevent from local wear and subsequent damages. In addition, advance built in grinding systems are used for rolls surface modification in dead time intervals between rolling of various slabs. Implemented equipment increases both product quality and milling line efficiency and decrease roll consumption. The primary condition for optimum usage of such advanced equipment is modeling roll wear phenomenon and calculating the amount of wear for correctly prediction of grinding execution time.

II. WEAR PHENOMENON

Roll wear in milling process, which is in fact roll weight reduction during milling process, is due to roll surface particle removal during roll contact with rolled metal. According to friction fundamental law, wear is directly related to friction force and this force is directly related to two main parameters including coefficient of friction and pressing force between two contacting surface. Due to this fact, the most important part of wear phenomenon modeling is rolling force and friction magnitude evaluation. Roll wear not only decreases slab profile quality, but interfere with functional accuracy of shape control system in rolling process and cause problem in other controlling systems calculations. Moreover, its effect on roll erosion is visible and sometimes contributes to roll damage and early fracture which has a negative effect on final product price.

Wear is gradual substance removal from material surface during forming process which is the result of relative motion between tools and material. In fact, wear does the same as friction does in mechanics. Wear depreciates forming tools, material, and its surface in milling process as friction dissipate energy and cause active forces losses in mechanics.

Active roll wear changes profile of rolls entrance and subsequently that of product. The effect of wear on active rolls after several milling processes is visible. This effect decreases roll diameter, however this diameter reduction is not uniform in roll longitudinal direction and is related to rolled slab width. Since rolled slabs thickness are not equal, changing slab thickness will contribute to roll surface wear profile changes which after a number of milling processes roll surface shape changes complicatedly. Moreover, there are other phenomena in milling process such as roll deflection due to rolling force and roll expansion due to temperature increment. Effects of these phenomena with those of wear phenomenon on roll entrance profile, contribute to slab profile forming.

III. HOT STRIP MILL LINE OF MOBARAKEH STEEL COMPANY

Hot strip mill line is one of the most important production sections of Mobarakeh Steel Company which was exploited with nominal capacitance of 2.5 million tons per year in 1993. Produced slabs in continuous casting unit enter this line and get arranged and stored based on three parameters, width, quality, and length. Afterwards, slabs are transferred to preheated chimneys and get rolled after preheating in hot strip mill line and change into a coil. Hot strip mill line control system of Mobarakeh is universal data management system. This system includes the whole data about raw materials, products, consumed material and energy and etc. which is linked to computers of that production line. This system gives necessary information to those computers and receives and analyzes all production parameters. Hot strip mill line of Mobarakeh Steel Company starts from the end of chimneys and continues to exiting coil conveyor. This line consists of four sections as following (Fig. 1):

(i) Preliminary (roughing) mill
(ii) Final (finishing) mill
(iii) Cooling section
(iv) Colliers

As an example roll features of finishing mill section are introduced in the following section.

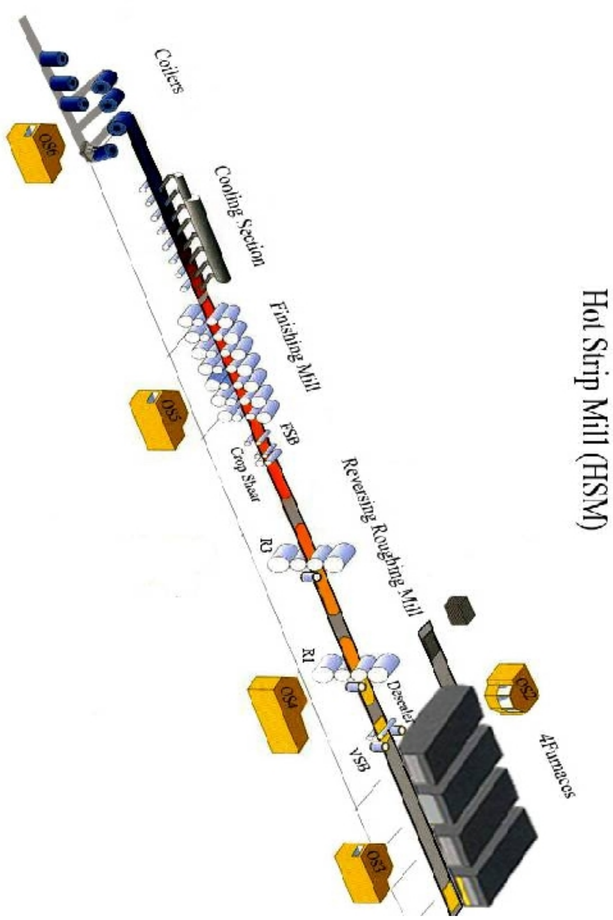

Fig.1. Hot strip mill line schematic of Mobarakeh Steel Company.

IV. FINISHING MILL

This is the most important part of milling process. A cutter is mounted on bar at the beginning of this part which is responsible for cutting unused parts of two ends of the bar. Afterwards, the bar gets rolled at seven continuous shelves until it reaches desired thickness and turn into a slab. Bar enters finishing mill section with temperature about 1100°C and exits as a slab with temperature about 900°C after rolling. There are seven four-roll shelves in this section which are mounted with 5.5m distance of each other. Features of these shelves are listed in Table 1.

Table 1: Finishing mill shelves features.

Roll number	Maximum roll diameter (mm)	Minimum roll diameter (mm)
F1	720	700
F2	735	715
F3	750	730
F4	765	745
F5	685	660
F6	705	680
F7	725	695

Reduction ratio in finishing mill shelves depends on entering bar thickness and temperature and exiting slab thickness. Subsequently, the speed of each shelve depends on exiting slab thickness and temperature. Calculations regarding shelves setting are done by milling process computers considering line conditions, entering bar, and exiting product.

V. MODELING OF ACTIVE ROLL WEAR IN HOT STRIP MILL UNIT

There are a lot of parameters contributing in roll wear process and evaluation of magnitude of wear without considering these parameters could cause error in results. Knowing this fact, the purpose of this section is to propose a mathematical model to evaluate roll wear profile of Mobarakeh Steel Company hot strip mill unit. Here is a model for worn roll profile evaluation. The model structure shown in Fig. 2 consists of two basic parts. In the first part, the calculation of rolling force magnitude is done and afterwards having results of evaluated force and other information, the roll profile is evaluated. Consequently, rolling force evaluation is prerequisite of wear evaluation.

This process is done continuously for each of rolled slabs in a milling program. Model inputs are physical and dimensional parameters of slabs milling program and rolls of each shelve which is explained in details in the following.

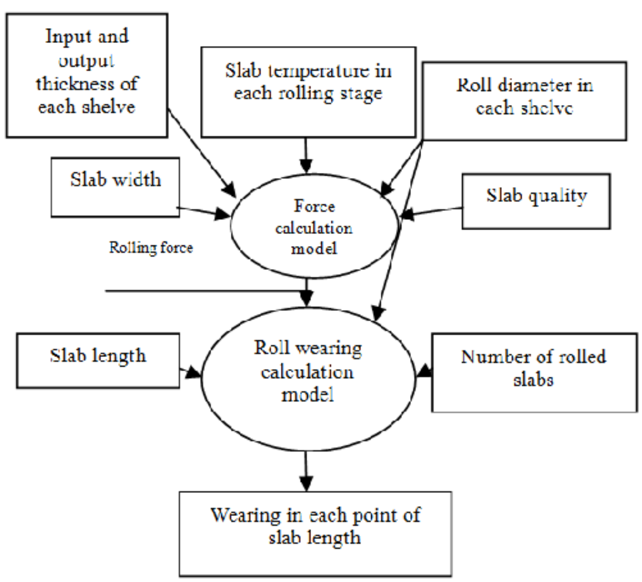

Fig. 2. Wear model flowchart.

VI. FORCE EVALUATION MODEL

Rolling force is one of the significantly important parameters in roll wear. Orowan and Pascoe [8] presented a simple way for rolling force evaluation, Bland and Ford [9], with Orowan theoretic basis and further assumptions, proposed a solution for rolling necessary force and moment. Sims [10] and Tselikov [11], assuming adhering and slipping friction in entire contact arc respectively, presented solutions for rolling force evaluation. El Kalay and Spraling [12] proposed more comprehensive relations based on Sims and Bland and ford models in 1968. Moreover, Alexander [13] in 1955, Ford and Alexander [14] in 1963, and Crane and Alexander [15] in 1968 proposed solutions utilizing slip lines method which was continued by Denton and Crane [16] in 1972 and Stahlberg [17] made a comprehensive review of these presented methods.

The difference between these theories is in assumptions made on friction variation manner in contact arc length and uniformity or non-uniformity of metal deformation on roll entrance. Comparing these methods, it turned out that the best method for rolling force evaluation is Sims'. Sims method for rolling force evaluation is an analytical-experimental formula. Here is summarized formula presented by Sims:

$$F = K\pi R\left(\sqrt{\frac{H}{R}}Sin^{-1}\sqrt{r}\right)+\frac{1}{2}Ln\frac{1}{1-r}-Ln\frac{h}{y}-\frac{\pi}{4}\sqrt{\frac{rh}{R}}$$

$$y = 2R(1-Cos\phi)+h$$

$$r = \frac{H-h}{H} \qquad \ldots(1)$$

In this relation K is magnitude of rolled metal flow stress in temperature of each stage of milling process, R is active roll diameter, r is relative thickness reduction, and y is slab squeezing magnitude in each stage of milling process. All of these parameters are known considering rolling geometry and are easily conceivable and reachable. The most important quality parameter is slab flow stress or K which depends on slab material and rolling temperature. This stress is obtained considering type of steel and its stress graph. The following relation is proposed for mean flow stress evaluation:

$$K = \exp\left(0.126-1.75[C]+0.594[C]^2+\frac{2851+2968[C]-1120[C]^2}{T}\right)\varepsilon^{0.21}\dot{\varepsilon}^{0.13}$$

In this relation [C] is percent of steel equivalent carbon density ε and $\dot{\varepsilon}$ and are respectively strain and strain rate of steel in milling process. In order to evaluate steel flow stress, firstly, the temperature of slab in each shelve should be evaluated which is accomplished by intelligent neural network models designed for this task. Afterwards, considering steel stress graph, flow stress magnitude is obtained for each stage of milling process [18].

In hot strip mill unit of Mobarakeh Steel Company, internal codes are used to show slab quality and material. So, in order to obtain model consistency with internal qualities, the same coding method, which is known as Mobarakeh standard method, has been used. Calculations concerning quality are done based on Mobarakeh internal codes and stored in data base. Consequently, after obtaining slab temperature in each stage of milling process, material flow stress is obtained based on its internal quality from data base. Using internal quality codes in Mobarakeh Steel Company, contribute to easier calculation of slab flow stress in different shelves. In addition, consideration of strain hardening in different stages of rolling increase calculation accuracy and make the program more user friendly for Mobarakeh staff.

VII. FORCE MODEL RESULTS ANALYSIS

Considering available data in hot strip mill line, the results of force calculation can be compared to force measured values which are sent to processing computers by load cells. To do so, gathered data during a couple of months, which was available in computers, has been extracted and data regarding those slabs has been sent to force model for calculation. The following graph shows the results of this comparison.

As shown in graph, obtained results from model is in good consistency with practical values which shows the reliability of the model. It should be noticed that measured values are related to old model data of hot strip mill line and only include biting time force. The error is sum of measurement and calculation errors. Moreover, since manual speed changing, even slightly, in one shelve change force value of that shelve and two neighbor shelves, the result of changing applied by operator should also be taken into account. However, this factor has not been considered in gathered data. Considering model reliability, rolling forces could be modeled and predicted by means of a program. The following figure shows evaluated rolling force by force model in milling program number 540 for finishing mill shelves.

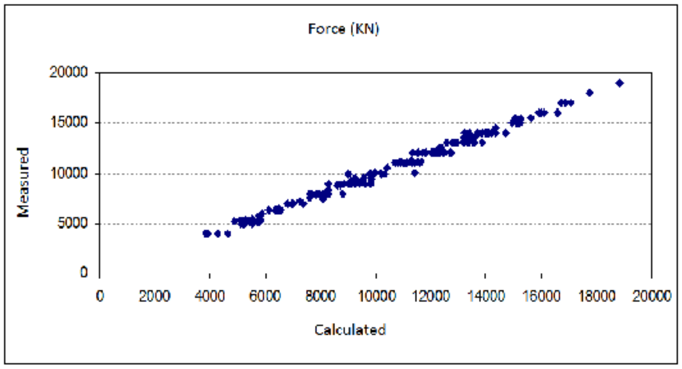

Fig. 3. Comparison between the results of force calculation and measured values of that.

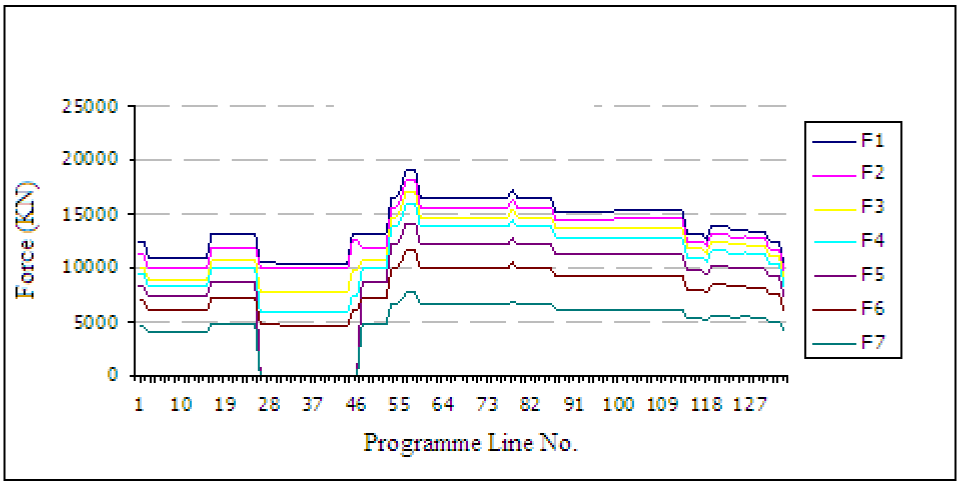

Fig. 4. Evaluated rolling force by force model in milling program number 540 for finishing mill shelves.

This graph shows rolling force during a specific program in finishing mill shelves. It should be mentioned that shelves loading is significantly influential in obtaining these graphs that changing one shelve load contribute to dramatic change of its force. Rolling operators, considering the situation, have to execute these changes. As an example, when rough noises or excessive flow is felt in one of the shelves, its load get reduced and that of other shelves increase. However, calculation basis is standard loading mode which is applied automatically by a computer. In such situation, maximum and minimum force are exerted on shelves F1 and F7 respectively which is consistent with shelves structure and milling process.

VIII. WEAR MODEL

Models proposed by Nakanishi [19] in 1985 are based on wear of the roll in contact with hot slab. Moreover, he showed that the amount of wear at slab edges is nearly 30% more than that of innermost regions (Fig. 5). The advantages of this method are its simplicity and calculation speed and disadvantages are low accuracy and neglecting wear of support rolls.

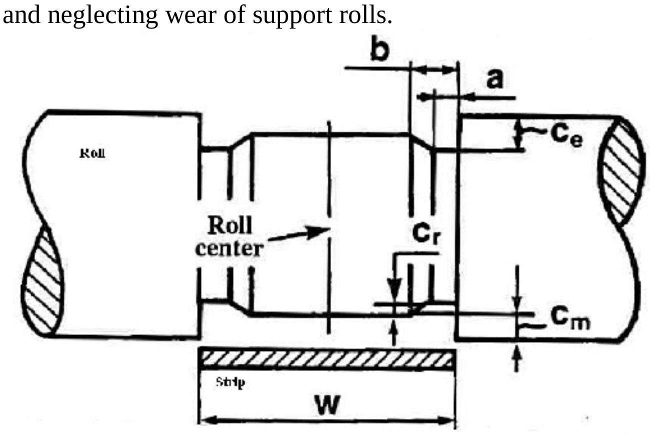

Fig. 5. A schematic of roll wear in contact with hot slab.

Oike [20] proposed a series of mathematical relations in 1977 for evaluation of the amount of wear based on milling shelve number, rolling force, width and length of contact, thickness reduction ratio, rolled slab length, active roll diameter, and experimental constants which depend on roll material, slab temperature, rolling lubrication, etc.

$$W = \sum_{i=1}^{n} \alpha \left(\frac{F_i}{w_i l_i} \right)^{\beta} (r_i l_i)^{\gamma} \frac{L_i}{\pi D + 2 f(x)} \delta(x) \quad \ldots(2)$$

$$\delta(x) = \begin{cases} 1 & if \quad -\frac{w_i}{2} \leq x \leq \frac{w_i}{2} \\ 0 & if \quad -\frac{w_i}{2} > x > \frac{w_i}{2} \end{cases}$$

Parameter x is introduced in Fig. 6 and L_i is the length of slab contact with roll at slab rolling time number i, which is calculated by the following relation:

$$l_i = \sqrt{\frac{D}{2} rH}$$

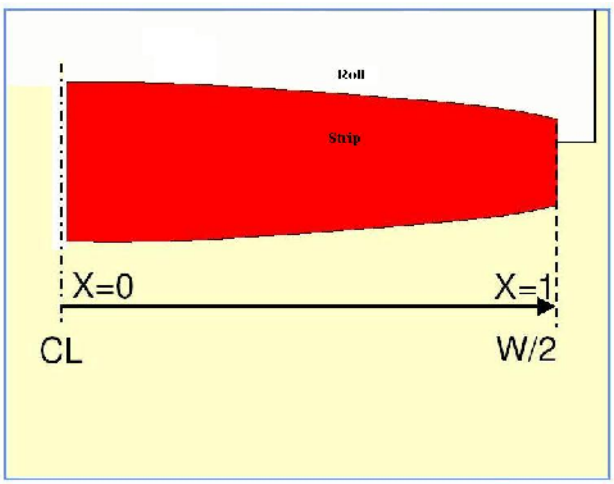

Fig. 6. A schematic of slab in contact with roll; x is measured from roll center.

The advantage of Oike method, comparing other methods, is its capability of wear distribution evaluation in roll length. However it still has some defects such as neglecting support roll wear and existence of numerous constants which should be calculated by experimental methods. Moreover, wear metallurgic effects are of least importance.

IX. OPTIMUM COEFFICIENTS CALCULATION OF ROLL WEAR RELATION

In previous section, an experimental relation has been obtained for roll wear in finishing mill shelves which has a number of constant coefficients. The best way to identify optimum coefficients of mentioned relation is utilizing practical data and finishing mill experimental results.

System identification method is used for unknown parameter identification of a system. In this method, which is one of the theoretical and practical branches of control theory, by having system behavior, inputs identification, and outputs measurement, system unknown parameters can be identified. System inputs are variants of equation (1) and its output is wear factor in milling shelves. Coefficients of equation (1), α, β, and γ, are system unknown parameters which should be identified.

In order to identify mentioned system unknown parameters, the outputs related to different inputs should be measured. Putting together the relations obtained from equation (2), a matrix-form equation is formed, the right side of which is output matrix and the left side of which is a mixture of coefficients and inputs matrix. Eventually, unknowns matrix is evaluated form mentioned matrix relation. The following relation is general form of mentioned matrix-form equation:

$$Y \begin{Bmatrix} \alpha \\ \beta \\ \gamma \end{Bmatrix} = W \quad \ldots(3)$$

Consequently, knowing W and Y sets, the purpose is identification of optimum coefficients α, β, and λ. Approximation theory is undoubtedly one of the best methods for optimum coefficients identification of an approximated equation. According to this method, if W is approximated in equation (3), sum of errors squared between desired and approximated values is defined as follows:

$$\begin{cases} \frac{\partial SSE}{\partial \alpha} = 0 \\ \frac{\partial SSE}{\partial \beta} = 0 \\ \frac{\partial SSE}{\partial \gamma} = 0 \end{cases} \quad \ldots(4)$$

This system of equations includes three nonlinear equations. Consequently an m-equation three-unknown system of equations is obtained which has to be analyzed using one of the equation solver methods numerically or in optimization form which results in α, β, and λ evaluation. These equations can be solved easily utilizing MATLAB optimization toolbox, which implements least square nonlinear equation solving method using Newton algorithm and Gauss elimination method [21, 22, 23, and 24].

X. WEAR MODEL RESULTS ANALYSIS

Gathering wear data of hot strip mill active rolls, the amount of wear and even worn rolls profile are obtained. This data should be used in both wear model calculations and constant coefficients identifications mentioned before. So, lots of data regarding used rolls should be available which requires a lot of time.

Firstly, the method of used roll profile measurement should be explained. Roll profile measurement is done in roll section of hot strip mill unit. A newer grinding machine, HERKULES brand, is used for the last three shelves which are more sensitive. This full automatic machine is equipped with measurement sensors and is controlled with advanced software. Putting cooled rolls in this machine, firstly, measurement sensors evaluate roll diameter and the amount of its wear and subsequently control system programs grinding stages. Finishing grinding stages, ground roll final profile is measured and registered in the system. This piece of equipment maintains final graphs automatically for further analysis. In order to register worn rolls primary graphs, grinding machine operator saves these graphs on the system or printer after primary measurement.

Grinding and measurement for primary shelves are done in a complete different way. In this roll manufactory four half automatic grinding machines are mounted for rolls grinding. Entering the cooled roll to these machines, the operator firstly measures diameter of rolls in three points using a micrometer. It evaluates the amount of wear and necessary amount of grinding and sends necessary number of pulses to system. Afterwards, machine grinds the roll considering defined passes and produces final profile. Working with these grinding machines needs more skill and precision in comparison with full automatic ones. Manual or digital bound gauges are used to measure these rolls profile. These pieces of equipment measure roll profile and show the results manually or using a computer program. In roll manufactory of Mobarakeh Steel Company hot strip mill unit, a digital bound gauge named CADNO2000 is used. This piece of equipment measures rolls profile and saves their data on memory cards which are read by software and related graphs are saved on the system or printed on a paper. In order to have access to worn mill profile, this profile should be measured by bound gauge before grinding. Moreover, primary profile of that roll, before milling process, should be measured in order to evaluate wear in milling process by comparing these two wear graphs.

Considering presented explanations, wear measurement of primary four shelves is done manually which is of lower accuracy than that of final shelves which is done automatically. Here are graphs taken of used and unused (before rolling) rolls:

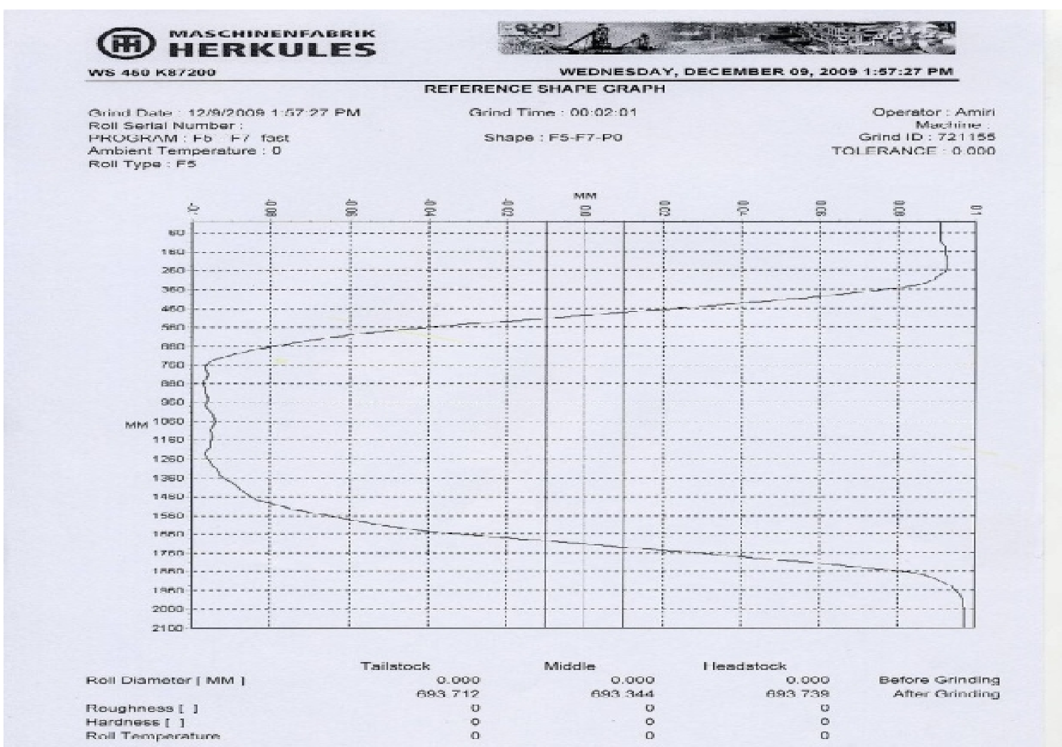

Fig. 7. Graph sample of F6 roll profile.

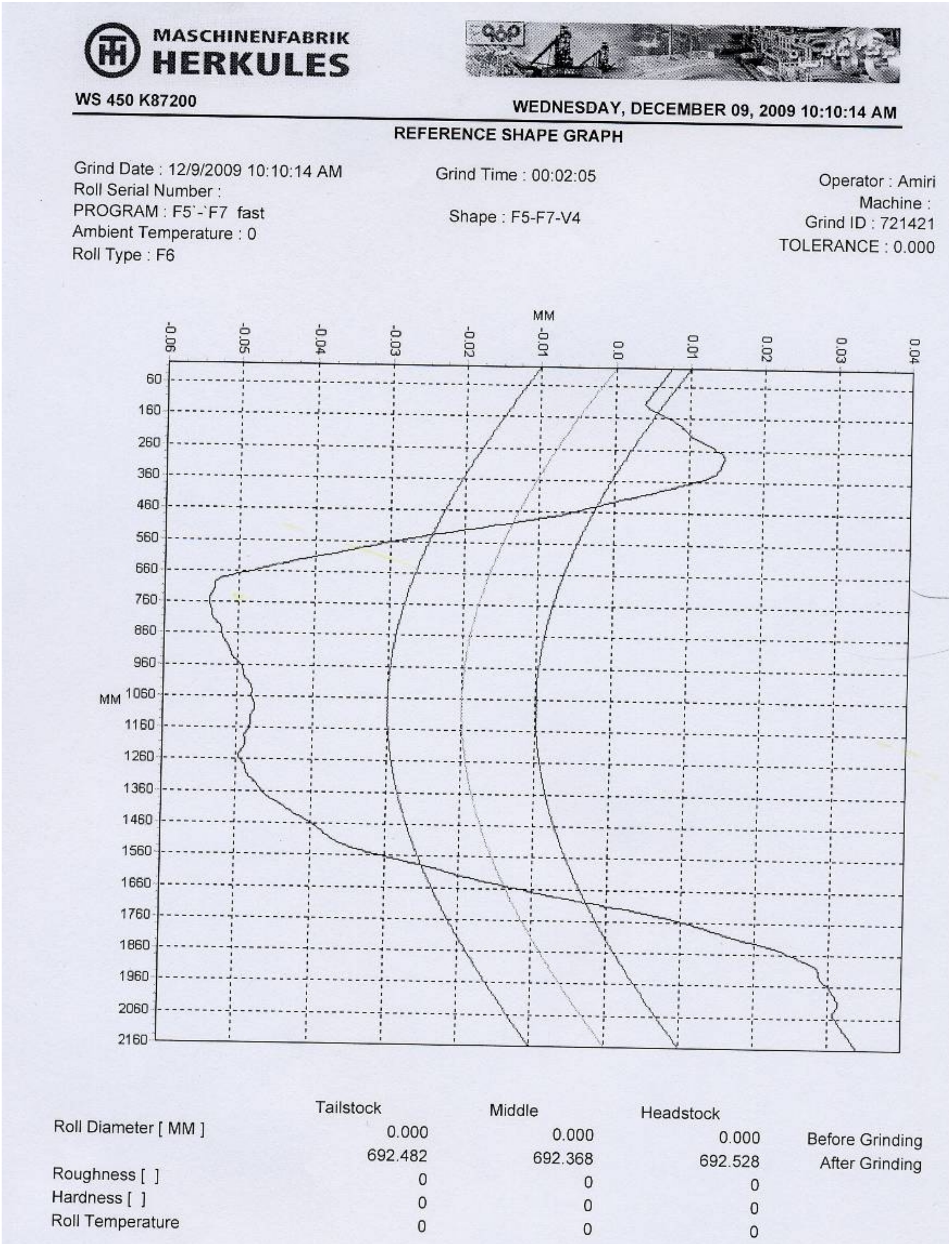

Fig. 8. Graph sample of F7 roll profile.

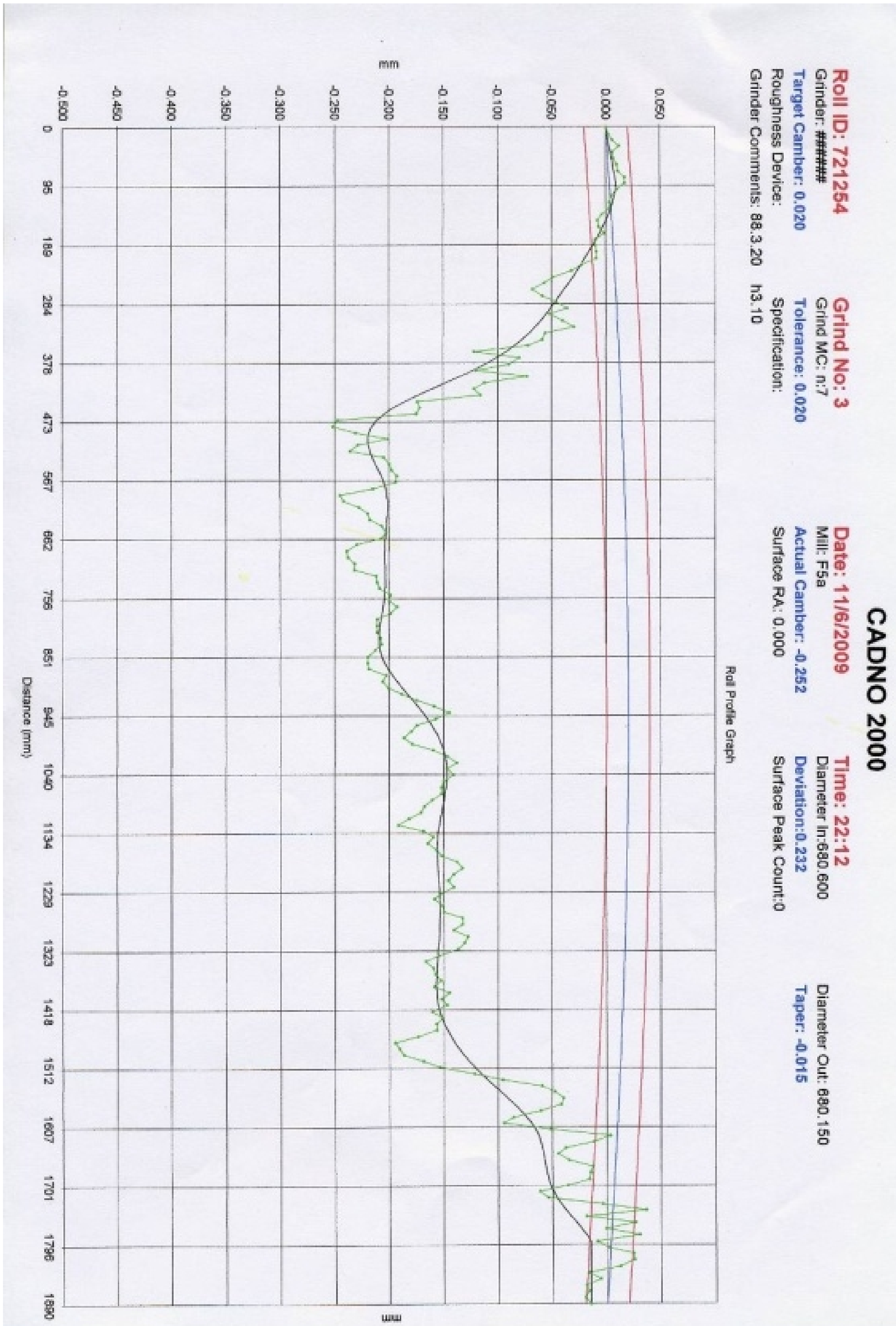

Fig. 9. Graph sample of F5 roll profile.

Above graphs are presented as samples of measurements done in hot strip mill unit active rolls. These measurements are done to gather data for regulation and optimization of coefficients used in model and also to check calculation results of implemented model. The following graphs illustrate a sample of wear model results in active roll wear calculation during milling program number 317 in different shelves of finishing mill. In order to compare model results with practical values, measurements are done for various shelves in a number of milling programs, results of which are shown in the following figure:

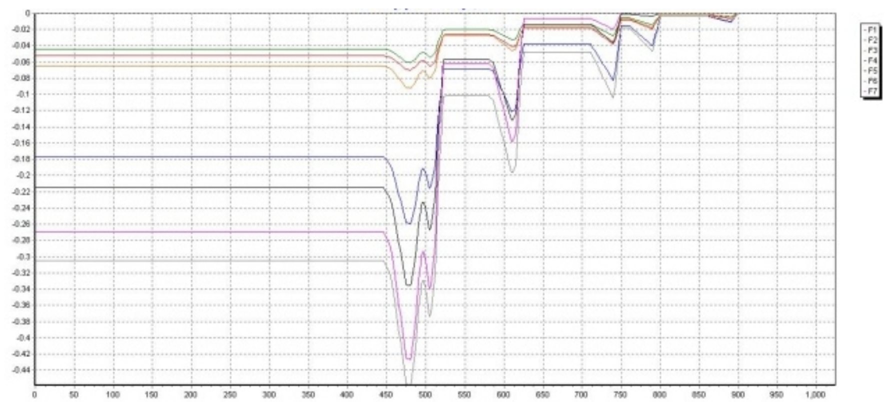

Fig. 10. A sample of wear model results in active roll wear calculation during milling program number 317 in different shelves of finishing mill.

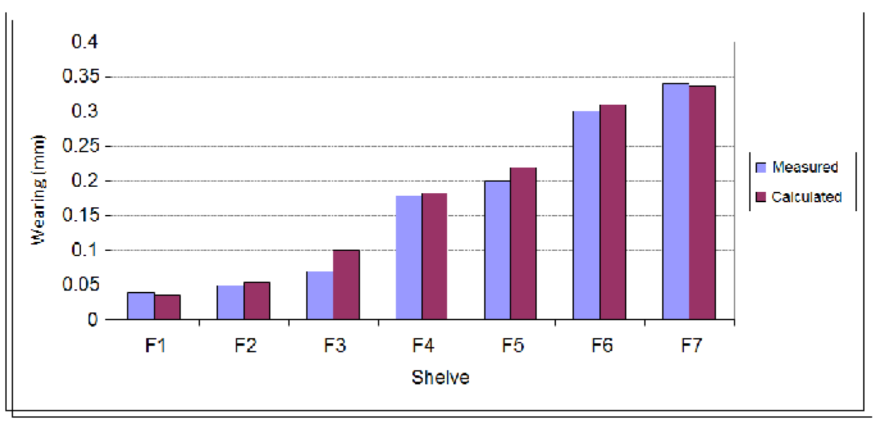

Fig. 11. Comparison of model results with practical values for various shelves in a number of milling programs.

XI. CONCLUSION

As shown in the last graph, there is a good consistency between model results and practical values which means the model predicts roll wear reliably. However, this is done only in standard situations. As mentioned in force model, even the slightest deviation from standard situations could result in different calculation results comparing to practical values. So, it shouldn't be expected that the results be identical in different situations.

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