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NUMERICAL MODELLING OF THE WORKING ROLLS WEAR DURING RODS ROLLING PROCESS

NUMERYCZNE MODELOWANIE ZUŻYCIA WALCÓW PODCZAS PROCESU WALCOWANIA PRĘTÓW

Numerical modelling of the round bar rolling process, while considering the wear of the passes depending on their shape, was carried out within the present work. For the theoretical study of the rolling process, the Forge2008® was employed, which is finite element method-relying software that enables the thermomechanical simulation of rolling processes in a triaxial strain state. The wear model implemented in the Forge2008® permits no quantitative evaluation, but only comparative analysis of the wear of rolls. In order to use the results of simulation employing the simplified Archard model for the quantitative evaluation of roll wear, it is necessary to define the wear factor and hardness of the tool as a function of temperature. The paper present a methodology for the determination of the quantitative wear of rolls based on the results of computer simulations performed using the Forge2008® software for a selected oval pass during rolling of round bars.

Keywords: wear, rolling, round bar, FEM, Archard's model

W pracy przeprowadzono numeryczne modelowanie procesu walcowania prętów okrągłych z uwzględnieniem zużycia wykrojów w zależności od ich kształtu. Do badań teoretycznych procesu walcowania zastosowano program komputerowy Forge2008®, który oparty jest na metodzie elementów skończonych i pozwala na termomechaniczną symulację procesów walcowania w trójosiowym stanie odkształcenia. Model zużycia stosowany w programie komputerowym Forge2008® nie pozwala na ilościową ocenę zużycia walców a jedynie na analizę porównawczą. W celu wykorzystania wyników symulacji z zastosowaniem uproszczonego modelu Archarda, do ilościowej oceny zużycia walców, konieczne jest zdefiniowanie współczynnika zużycia i twardości narzędzia w funkcji temperatury. W pracy przedstawiono metodykę wyznaczenia ilościowego zużycia walców na podstawie wyników symulacji komputerowych wykonanych za pomocą programu Forge2008® dla wybranego przepustu owalnego podczas walcowania prętów okrągłych.

1. Introduction

The continuous rolling of long products can be ranked among the most efficient processes that enable a long product of high mechanical and strength properties and good surface quality to be obtained within a narrow dimensional tolerance range [1]. The dimensional accuracy of finished product is dependent on the applied shapes of a set of passes successively mating with one another. These passes wear during operation, which affects the dimensional accuracy of the finished product and the run of the rolling process [1-3]. The roll wear (abrasion and roll groove burning out) is a particularly important problem in the process of ribbed bar rolling using the longitudinal strip separation technology [1,2]. The implementation of this technology involves usage of special separating passes in the rolling line, which will form the strip into separate strands that will be subsequently separated on idle separating rollers. The wear of the separating passes results in a change in the cross-section of the strip, especially that of the bridge(s) connecting individual strands, which, as a consequence, may lead to the strip being wedged in the separating box and a break in the continuity of the process [2]. Therefore, the determination of the magnitude of pass wear in the rolling process can prevent many difficulties encountered while running this process, and assure obtaining finished product meeting the requirements of applicable acceptance standards. So, determining the quantitative wear of the rolls (changes in the geometry of the rolls during their operation) will make it possible to establish their service life or the mass of finished product complying with the dimensional tolerance requirements.

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A methodology for the qualitative and quantitative determination of the oval pass wear during rolling of 20 mm-diameter bar is presented in the paper. For determining the wear of the rolls, the results of numerical computation of the unit roll friction force work were used, which was performed using FEM-based computer program, as well as empirical computation and experimental tests carried out in one of Poland's continuous bar rolling mills.

2. Purpose and range of research

The purpose of the work was to determine the value of the roll (pass) wear factor in the shape rolling process and to determined the actual wear of the passes in this process.

Moreover, the aim of the work was also to verify the roll wear magnitude obtained from the numerical modelling based on the actual change of the oval pass shape.

Within the investigation, a theoretical study of the process of rolling a 24 mm-diameter preform in the oval pass (Fig. 2) was carried out. Based on the performed numerical studies, the unit friction force work was determined, which was necessary for determining the roll wear. The numerical modelling of the rolling process was performed for rolling stand no. 16 of the D380 continuous bar rolling mill. Figure 2 presents a schematic of the continuous round bar rolling mill, while Figure 2 shows the shape of an oval pass turned on the rolls in rolling stand no. 16.
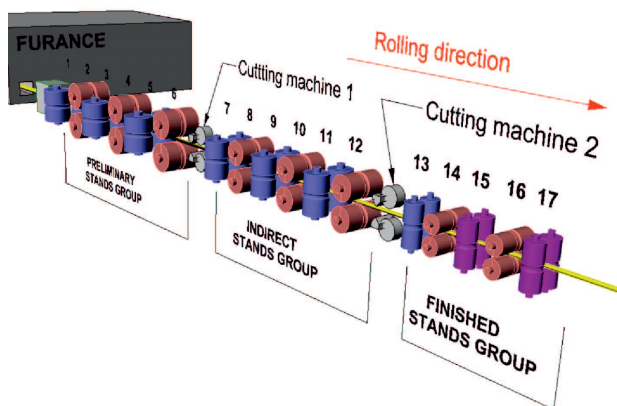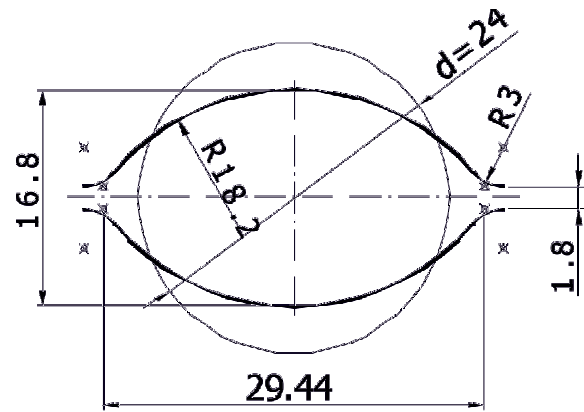

Fig. 2. Shape and dimensions of the oval groove in 16th stand

The numerical modelling of the process of rolling from the 24 mm-diameter round strip into an oval strip in rolling stand no. 16 was run at an average temperature of 950°C. The temperature of the round strip before rolling stand no. 16 was determined based on the results of pyrometric measurements taken during actual rolling. To enhance the accuracy of numerical computation, simulation of strip cooling before rolling stand no. 16 was made. The cooling process was continued until the moment when the strip surface temperature corresponded to the temperature measured on the rolled strip surface under industrial conditions. In accordance with the data recorded during actual rolling, the following were taken for the simulation: rolling speed, 6.5 m/s; rolls diameter, 375 mm; friction coefficient, 0.4 [4]; heat transfer coefficient, 3000 W·K^{-1}·m^{-2} [4]; rolled steel grade, C4D. The yield stress of steel C4D was taken from the material database of the Forge2008 program, and was entered to the computer simulation in the form of a function described by the Hansel-Spittel equation (1), which was characterized by the following coefficients: $A_0 = 716.6475$; $m_1 = 0.00219$; $m_2 = 0.1523$; $m_3 = 0.13792$; $m_4 = 0.0486$ [4,5]. Figure 3 illustrates the variation of the yield stress for three strain rates at a temperature of 950°C.

$$\sigma_p = A_0 e^{-m_1 T} \varepsilon^{m_2} \dot{\varepsilon}^{m_3} e^{-m_4 \varepsilon} \tag{1}$$

where: T – temperature, $\dot{\varepsilon}$ – strain rate, ε – strain, A_0, $m_1 - m_4$ – coefficients of steel properties.

To reduce the computation time, the computation was completed for ¼ of the rolled strip cross-section.

Experimental tests were carried out within the work, which included the determination of the actual wear of the oval pass turned on the rolls of rolling stand no. 16. The change of the strip dimensions was determined based on specimens rolled out from aluminium Al99.9. The specimens were prepared in the form of 26 mm-diameter round bars. The use of a larger aluminium

Fig. 1. Schema of continuous rolling mill to the rolling round bar

bar diameter compared to the steel preform was aimed at mapping the entire pass contour together with the roll gap. An important aspect in determining the pass wear is the knowledge of the change in the roll gap during the rolling campaign. This gap is reduced as the rolling campaign progresses in order to maintain the proper strip shape. The shape of the oval pass was mapped two times: at the beginning of the rolling campaign and after rolling out of 1728 Mg of bars. In the experimental rolling tests, low-carbon steel grades of a carbon content from 0.05% to 0.08% were used. Table 1 contains the percentage fractions of particular steel grades relative to the total amount of steel rolled out in the oval pass.
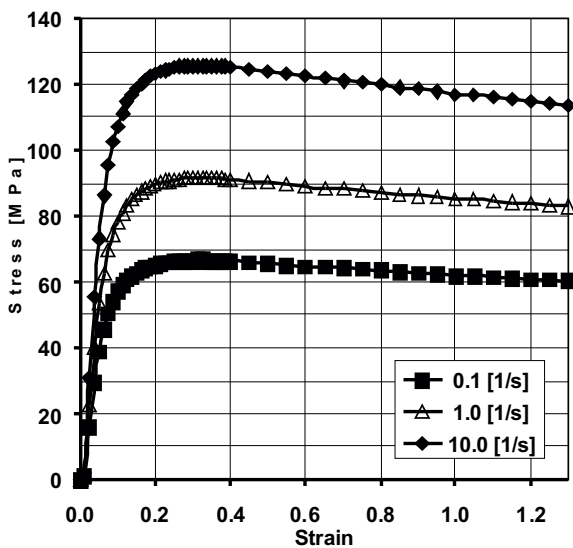

Fig. 3. Yield stress dependent on strain and strain rate for the C4D steel – 950°C

TABLE 1

Fraction of steel grade in all feedstock used to the rolling process – 1728 Mg

Grade of steel	SpG1A	C4D	C4D1	1006	1011	17MnB3	43Si1
Percentage fraction [%]	21.9	5.4	13.8	30.4	10.4	4.0	14.1
Mass of steel grade [Mg]	378.43	93.31	238.46	525.31	179.71	69.12	243.65

3. Mathematical model use during numerical modelling

The groove rolling process is described by the tri-axial stress and strain pattern. It is therefore difficult to describe using straightforward empirical relationships. To perform the analysis of the plastic flow of metal in the deformation zone it is necessary to solve the system of the plasticity theory's equations, which includes geometrical relationships, physical equations and equilibrium equations, in which rolling process conditions must be allowed for [1,2].

For the simulation of the three-dimensional plastic metal flow during rolling of a round bar in the oval pass, a mathematical model was employed, in which the mechanical state of the deformed material is described by the Norton-Hoff law [4, 6, 7]:

$$S_{ij} = 2K(T, \dot{\bar{\varepsilon}}, \bar{\varepsilon})(\sqrt{3}\dot{\bar{\varepsilon}})^{m-1}\dot{\varepsilon}_{ij}. \qquad (2)$$

where: S_{ij} – stress tensor deviator; $\dot{\bar{\varepsilon}}$ – strain rate intensity; $\dot{\varepsilon}_{ij}$ – strain rate tensor; $\bar{\varepsilon}$ – strain intensity, T – temperature, K – consistence dependent on the yield stress; σ_p, m – factor characterizing hot metal deformation ($0 < m < 1$).

The wear of the tools occurs during the plastic working of metals. The wear type that most commonly occurs in these processes is abrasive wear [2, 3]. For the description of abrasive wear, Archard's model is often used [8]. It is assumed in this model that, under abrasive wear conditions, V_z of material separated from the unit tool surface is directly proportional to the normal stress, σ_n, acting on tool surface and to the friction path, L_t, and inversely proportional to the hardness H of the material undergoing wear (in this case the tool hardness). This model can be written in the following form:

$$V_z = k_w \frac{\sigma_n L_t}{H}. \qquad (3)$$

where: k_w – wear coefficient.

Equation (3) can be presented in the integral form to be solved using an FEM-based algorithm:

$$V_z = k_w \int_0^t \frac{\sigma_n v_s}{H(T)} dt, \qquad (4)$$

where: v_s – tangential velocity of metal slip over the tool surface; t – time; $H(T)$ – tool hardness at specific temperature.

The parameters σ_n, v_s and T are regarded as variable for any point on the tool surface during the plastic working process. These parameters were determined using a finite element-based three-dimensional mathematical model, in which the mechanical state of the deformed material was described using the Norton-Hoff law [4, 6, 7].

For solving Eq. (4), the value of the wear factor, k_w, and the tool hardness, H, must be known. To determine the tool hardness H, it is necessary to determine the factor allowing for the effect of tool temperature on the hardness. Therefore, the exact quantitative analysis of tool wear is only possible after obtaining appropriate

498

empirical data and determining the empirical coefficients in Eq. (4).

Neglecting the effect of the wear factor k_w and the effect of temperature on the tool hardness allows Eq. (4) to be used for comparison purposes only. Therefore, in the model employed in the Forge2008® program, Eq. (3) has been simplified to the following form:

$$W = \int_0^t \sigma_n v_s dt. \qquad (5)$$

As the friction stress, τ_j, is the product of the normal stress, σ_n, and the friction coefficient, μ [4, 8], hence the integral:

$$\int_0^t \sigma_n v_s dt \qquad (6)$$

has a physical meaning and is equal to the friction force work per unit metal-to-tool contact surface.

The wear model implemented in the Forge2008® program does not permit tool temperature changes to be allowed for, and does not enable one to define the properties of the contacting surfaces of the deformed metal and the tool [2, 4]. To be able to quantitatively determine the wear of the tools, Eq. (4) should be transformed to the following form:

$$V_z = \frac{k_w}{HV} \int_0^t \sigma_n v_s dt, \qquad (7)$$

where: HV – Vickers hardness.

Assuming that in the rolling process the hardness of the cast iron rolls does not depend on their temperature (the tool hardness in the temperature range of 20-100°C may actually undergo insignificant changes), the expression $H(T)$ in Eq. (4) can be taken outside the integral symbol. After transferring the expression $H(T)$ before the integral symbol, the expression of integration will define the unit friction force work. It the conducted tests, the hardness of the cast iron rolls were assumed to be 480 HV. This hardness was taken from the technical specification of the rolls, as supplied by the roll manufacturer.

In Equation (7), an important factor influencing the wear magnitude is the factor k_w. In available technological literature, this factor attains values in the range from

$0.5 \cdot 10^{-5}$ do $0.8 \cdot 10^{-7}$ mm$^3 \cdot$mm$^{-1} \cdot$mm^{-2} [9-11], depending on the conditions of tools used. In order to more accurately determine the wear factor k_w, experimental tests of the rolling process in industrial conditions were undertaken.

4. Results of theoretical and experimental researches

As a result of the numerical modelling of the process of rolling the 24 mm-diameter preform in the oval pass (Fig. 2.), a strip was obtained, as shown in Figure 4.
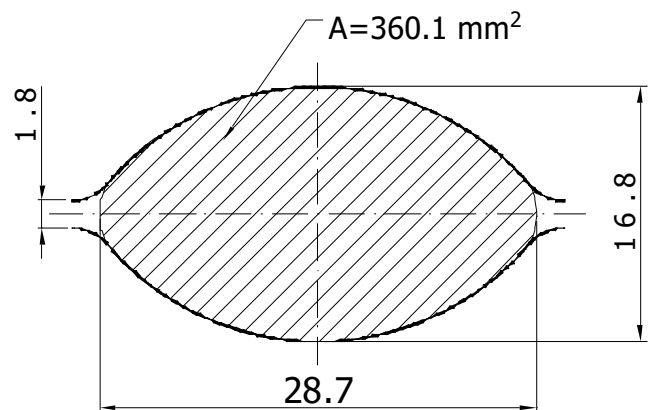

Fig. 4. Shape and dimensions of the oval band obtained in numerical modeling rolling process

When comparing the shape of the oval strip obtained from computer simulation with the shape of the strip obtained from the actual rolling process, whose dimensions were 16.8×29.1 mm, it can be found that a satisfactory accuracy of the numerical computation was achieved. The dimensions of the oval strip rolled under real conditions were measured at the beginning of the rolling campaign that is when rolling in the pass of the nominal dimensions.

Based on the results of the numerical modelling of the process of rolling in the oval pass (stand no. 16) it was possible to determine the distribution of the friction force work on the working surface of the oval pass. The distribution of unit friction force work on the surface of the roll after one revolution is shown in Figure 5a.
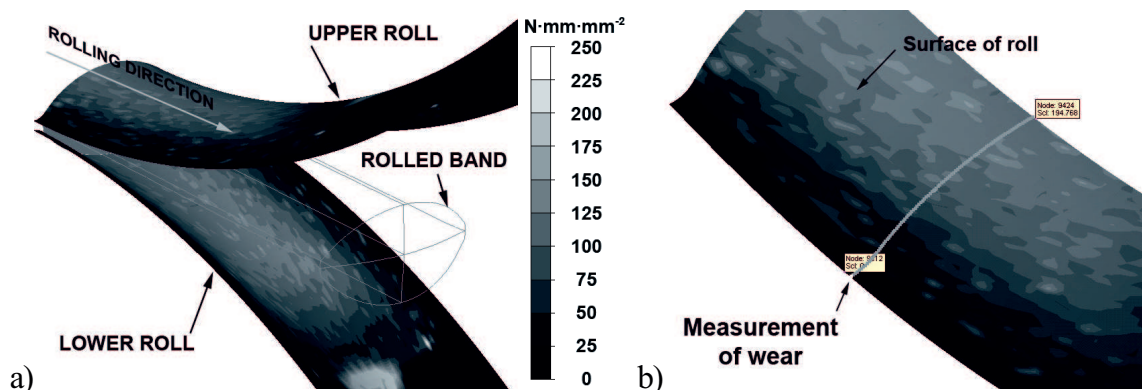
Fig. 5. Distribution of the oval unit friction force work during rolling process: a) distribution of unit friction force work on the roll surface, b) method of measurement (half of roll)

On the basis of the performed computer simulation it was possible to determine the distribution of unit friction force work over the roll surface. In Figure 5b, a schematic for the measurement of unit friction force work on 1/2 of the roll width is shown. Figure 6 shows the obtained values of unit friction force work over the width of the pass. These values are the means obtained for three measurement lines on strip exit from the deformation zone (Fig. 5b).
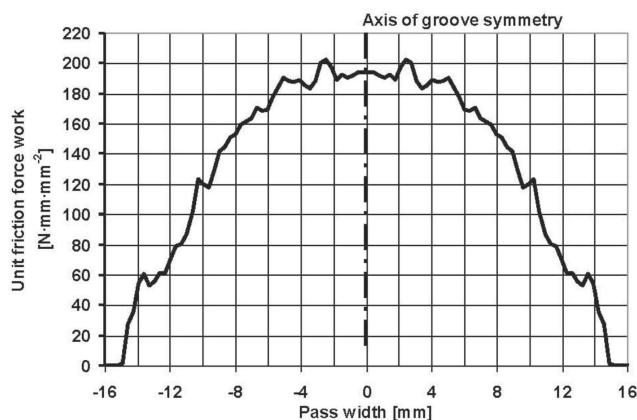

Fig. 6. Distribution of average unit friction force work on the oval groove after one revolution of roll

Based on the results of the theoretical study it can be found that during rolling of round strip in the oval pass the highest values of unit friction force work (approx. 200 N·mm·mm^{-2}) occur in the middle part of the pass and they decrease with increasing distance from the axis of symmetry of the pass. Due to the fact that the oval pass was not completely filled during rolling, in the locations of transition of the groove to the flat roll part the obtained unit friction force work values were close to 0.

The next stage of the work included carrying out of experimental tests which enabled the determination of the shape of the pass after the rolling campaign. The determination of the loss of the roll volume (pass wear) was possible based on the measurement of the geometry of the rolled aluminium specimens, which had been used for the experimental tests. Using these specimens, the shape of the pass was reproduced at the beginning of the rolling campaign and after rolling out of 1728 Mg of low carbon steel. The specimen cross-section shapes are shown in Figure 7.

The change of the strip cross-section shape and of the roll volume loss was determined in a CAD type program. The roll volume loss, ΔV, after rolling out of 1728 Mg of finished product amounted to 112339 mm^3. The obtained data allowed the determination of the wear factor, k_w, from the relationship:

$$k_w = \frac{\Delta V}{n_r \cdot ld \cdot A_{ld}}[\frac{mm^3}{mm \cdot mm^2}], \qquad (8)$$

where: n_r – number of roll revolutions during rolling of 1728 Mg of rods, 590441 rot.; ld roll gap length, 35.5 mm; A_{ld} – area of metal-to-roll contact surface, as determined using a CAD type program, 794.2 mm^2. Substituting the obtained data in Eq. (8), the wear factor, k_w, was calculated to be 6.74·10^6 mm^3·mm^{-1}·mm^{-2}.

The calculated wear factor, k_w, was then used for determining the quantitative wear of the rolls using Eq. (7). By substituting the obtained values of unit friction force work, roll hardness, and the calculated value of the roll wear factor, the theoretical shape of the pass after rolling out of 1728 Mg of bars was determined. In Figure 8, the theoretical oval pass shape as compared to the nominal shape (at the beginning of the rolling campaign) and the actual pass after completion of the rolling campaign (after rolling out of 1728 Mg of bars) is shown.
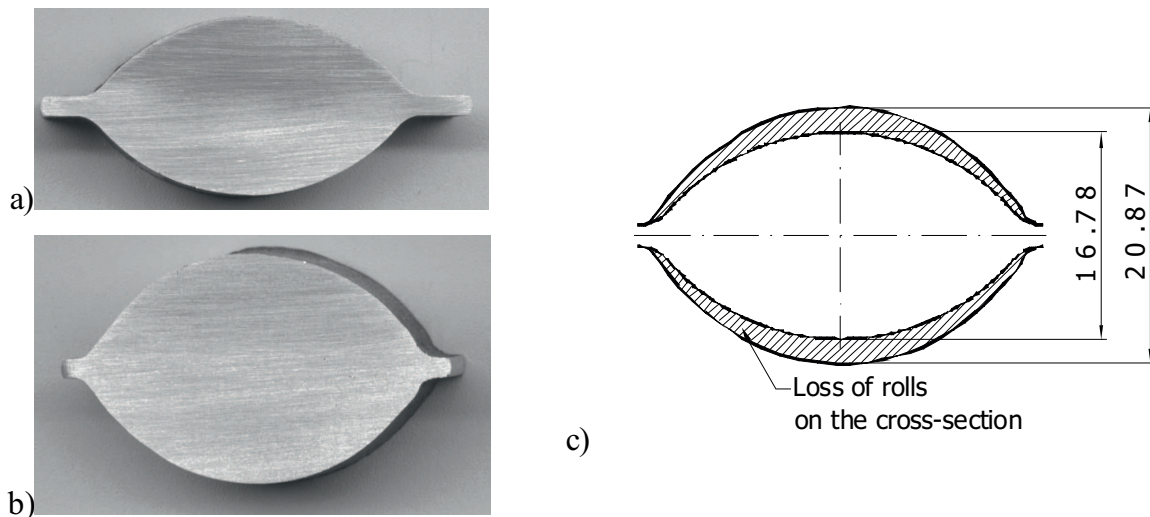
Fig. 7. Shape of aluminum samples representations of groove shape: a) on the beginning rolling campaign, b) after rolling 1728 Mg feedstock, c) loss of roll on the cross-section
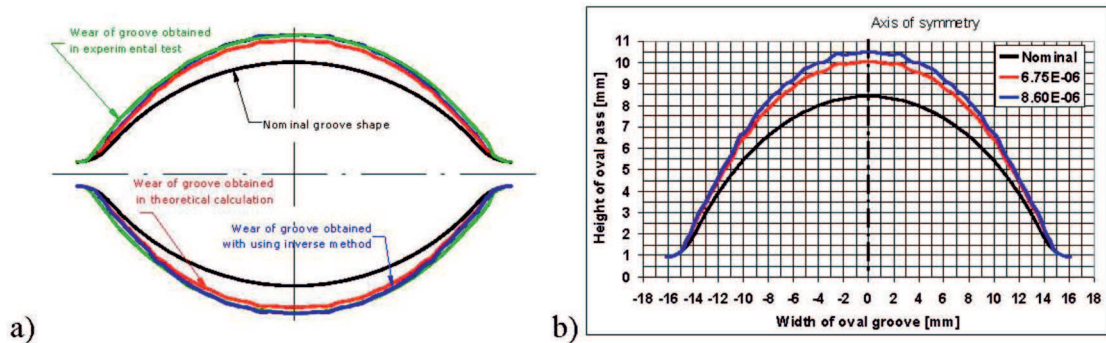

Fig. 8. Shape and dimensions oval groove after rolling out of 1728 Mg of finished product: a) wear of the oval groove compared with nominal groove shape, b) height of roll groove on the width of groove

Based on the studies carried out, the theoretical shape of the worn oval pass was determined, which is shown in Figure 8a. The pass contour determined using the wear factor value of k_w=6.74·10^{-6} mm^3·mm^{-1}·mm^{-2} is outlined with the red line. The oval pass shape obtained during rolling in real conditions is marked with the green line. Moreover, the pass wear, as determined by the inverse method, is indicated in Figures 8a and 8b with the blue line. Using the inverse methods, on the assumption that the unit friction force work had been determined correctly, the wear factor k_w was calculated for this pass to be 8.6·10^{-6} mm^3·mm^{-1}·mm^{-2}. With this value of the wear factor, the theoretical contour of the worn pass corresponds to the contour of the pass worn under real conditions. Comparison of the oval roll groove shape for both values of the coefficient k_w is demonstrated in Figure 8b.

When analyzing the data in Figure 8a it can be found that the pass wear in the location of pass groove transition to the flat roll part in the actual rolling process was slightly greater compared to that determined experimentally. The greater wear of the lateral pass parts in the actual rolling process might be due to the unsteady rolling process occurring at the beginning and at the end of the strip, where the magnitude of strip widening is greater compared to the remaining part of the strip.

The existing differences in the determined values of the wear factor k_w (6.74·10^{-6} and 8.6·10^{-6} mm^3·mm^{-1}·mm^{-2}) might be result (in the case of numerical modelling) of too small the computed value of unit friction force work. The work is dependent upon the yield stress. The yield stress was computed based on the data from the material database of the Forge2008® program. The determination of the yield stress on the basis of plastometric tests will increase

the accuracy of computations carried out. Moreover, the actual rolling of bars was conducted with several steel grades, whereas the numerical modelling of the rolling process was only carried out for one steel grade. For these reasons, inaccuracies occur in the computation results. A factor influencing the unit friction force work magnitude is also the friction coefficient that varies over the roll gap length, which, in the case of numerical modelling, is not allowed for. In the case of the actual rolling process, the wear factor determined based on the pass volume loss might be too small, since, aside from the classical abrasive wear, other phenomena also occur during hot rolling. Such phenomena may include erosion resulting from high temperatures and dynamic loads acting on the roll. The experimental tests were conducted in a continuous rolling mill, where tension forces occur during rolling of bars, which were not taken into account in the numerical computations.

5. Conclusions

On the basis of the performed experimental tests and theoretical computations, it was possible to determine the roll wear factor that enables the calculation of the quantitative wear of the rolls during the round bar hot rolling process with satisfactory accuracy.

The theoretical values of the roll wear factor computed based on experimental tests and by using the inverse methods are similar, and the difference between them is due to the use of several low carbon steel grades in the experimental tests, in contrast to the numerical rolling process modelling, where only one steel grade was taken for examination.

The roll wear factor obtained using the inverse method can be used in the Forge2008® program for the quantitative determination of the roll wear. The obtained results require, however, further theoretical studies and experimental verification for other pass types, steel grades and process parameters.

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