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ANALYSIS OF ROLLS WEAR DURING THE RIBBED BARS MULTI-SLIT ROLLING PROCESS

ANALIZA ZUŻYCIA WALCÓW PODCZAS WIELOŻYŁOWEGO WALCOWANIA PRĘTÓW ŻEBROWANYCH

An analysis of the roll wear in the multi-strand rolling of reinforced concrete ribbed bars has been made in the study. In the technology under consideration, the longitudinal partition of the band takes place in special slitting passes, while the separation of individual strands – in idle separating rollers. During rolling, the slitting passes undergo fast wear compared to the remaining passes of the rolling line. The paper reports the results of theoretical and experimental examinations, on the basis of which the wear of the slitting passes in the 16 mm-diameter ribbed bar three-strand rolling process has been determined. The theoretical examination was done using the Forge2011® software program, while experimental tests were carried out in a D350 medium-size continuous rolling mill. Based on the analysis of the investigation results, the wear coefficient was established for the slitting passes, which allowed the determination of their quantitative wear.

Keywords: groove-rolling, ribbed bars, wear, numerical modeling, FEM

W pracy przeprowadzono analizę zużycia walców podczas wielożyłowego walcowania prętów żebrowanych przeznaczonych do zbrojenia betonu. W tej technologii wzdłużny podział pasma następuje w specjalnych wykrojach rozdzielających a oddzielenie poszczególnych żył w nienapędzanych rolkach rozdzielających. Podczas walcowania wykroje rozdzielające ulegają szybkiemu zużyciu w porównaniu do pozostałych wykrojów linii walcowniczej. W pracy przedstawiono wyniki badań teoretycznych i doświadczalnych na podstawie których określono zużycie wykrojów rozdzielających w procesie trójżyłowego walcowania prętów żebrowanych o średnicy 16 mm. Badania teoretyczne wykonano za pomocą programu komputerowego Forge2011®, natomiast badania doświadczalne przeprowadzono w średniej walcowni ciągłej D350. Na podstawie analizy wyników badań określono współczynnik zużycia dla wykrojów rozdzielających, co umożliwiło wyznaczenie ich ilościowego zużycia.

1. Introduction

Constant demand for ribbed bars is observed in the world markets. The purchasers require the products to have the appropriate structure, shape and dimensions, which are dependent, inter alia, on the system of passes used for rolling. Also, a low price is expected [1, 2]. The reduction of ribbed bar manufacturing costs can be achieved, e.g., by employing the multi-strand rolling technology. During the ribbed bar rolling process with longitudinal band separation in the rolling line, individual passes within the rolling line are subject to wearing; in particular, the knife parts (combs) of the slitting passes undergo wearing, which affects the continuity of the rolling process and the dimensional accuracy of the finished products [3, 5].

The paper presents the results of theoretical and experimental examinations of the rolls (slitting passes) in the process of three-strand rolling of 16 mm-diameter ribbed bars. For the theoretical examination of the process of ribbed bar rolling with longitudinal band separation, Forge2011®, a finite element method-based software program, was used, which enables the thermo-mechanical simulation of the processes of rolling in a triaxial strain state [7-9]. The Archard wear model implemented in the Forge2011® program does not allow the quantitative assessment, but only a comparative analysis of the roll wear to be made [5, 10-15]. For the quantitative roll wear assessment, in addition to computer simulation results, the determination of the roll wear coefficient is also needed [11, 12]. For this purpose, experimental examinations were carried out under industrial conditions, which allowed the determination of the actual wear of the passes after a rolling campaign. The examinations involved the mapping of the geometry of the pre-slitting and slitting passes prior to and after a specific mass of bars had been rolled. The shape of the worn passes was determined based on the test rolling of aluminium templates, which were subsequently transformed into a digital form with a 3D scanner. Using a CAD-type computer program, their cross-sections were made to take the measurement of their shape. The determined cross-sections enabled the determination of the variations in the shape and dimensions of the passes as compared to the nominal passes. The obtained test results provided the basis for determining the wear coefficient k_{w}, which was then used for the calculation of the quantitative roll wear using the Archard model.

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2. Technology of rolling bars with longitudinal band separation

In the process of rolling ribbed bars using the longitudinal band separation technology, the slitting pass wear (by roll groove abrasion and burnout) is an especially important issue. The determination of the magnitude of pass wear in this process can prevent many difficulties encountered when running it and ensure that a finished product is obtained, which meets the requirements of applicable acceptance standards. Determining the quantitative pass wear (changes in the geometry of the passes during their operation) will make it possible to establish their service life or the mass of finished product complying with the dimensional tolerance requirements.

Rolling of ribbed bars is normally done in continuous rolling mills. An example schematic of the rolling mill, in which the investigation was carried out, is shown in Figure 1. The rolling line is made up of 18 vertical stands divided into three groups: a rouging group, D550; an intermediate group, D450; and a finishing group, D350. The slitting passes, in which the preliminary separation of the band takes place, are situated as follows: in the rolls of Stand 15 – the pre-slitting pass, and in the rolls of Stand 16 – the slitting pass (Fig. 1). Past these passes, special separating rollers are positioned, in which the final longitudinal slitting of the band into separate strands takes place.

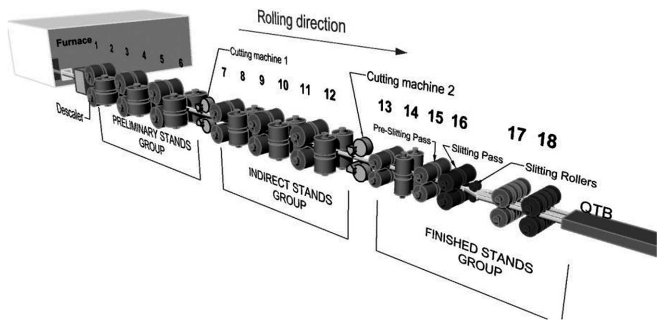


Fig. 1. Schema of continuous rolling mill D350 to the ribbed bars rolling

Feedstock for ribbed bar rolling is a 160×160 mm cross-section billet, which is rolled in box passes and then in stretching passes (the roughing stand group). Next, in the intermediate stand group, it is rolled out on flat rolls into a preform, which is an input band for the slitting passes in the finishing stand group. In the case of rolling 16 mm-diameter ribbed bars in the three-strand technology, the preform was 57.5×21.7 mm cross-section band.

An important stage in the multi-strand ribbed bar rolling process is the preparation of the cross-sectional shape of the band to be separated in the equipment boxes (to obtain the correct thickness of bridges connecting individual band strands). In most instances, this stage is carried out by a system of two slitting passes operating with each other [3-6]. The shapes of the pre-slitting and slitting passes used in the tests are shown respectively in Figure 2.

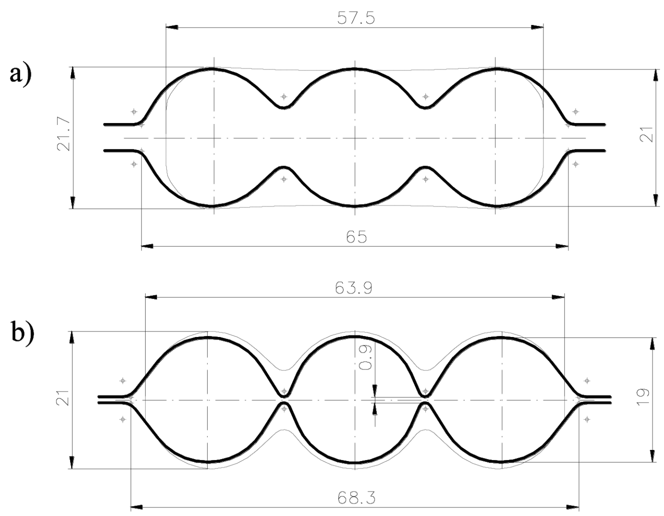


Fig. 2. Shape of the slitting passes to the 16 mm ribbed bars rolling process: a) pre slitting groove – 15th pass, b) slitting groove – 16th pass

3. Test material and its characteristics

The 16 mm-diameter ribbed bars are most commonly rolled with band separation from steel grade BSt500S (according to the Polish standard). A particularly important aspect of conducted tests is to ensure that the operation of the rolls is maintained under the same conditions, that is a specific steel grade is rolled with the remaining process parameters being constant. Chemical composition of the steel used for the tests is given in Table 1.

TABLE 1

The chemical composition of steel BSt500S, % mass

C	Mn	Si	P	S	Cr	Ni	Cu	V
0.21	1.40	0.45	0.04	0.04	0.25	0.25	0.25	0.13

The analysis of hot rolling processes using both empirical formulas and numerical examination, in which the finite element method is used, is dependent on the correct determination of the curves of the plastic flow of the examined material [7, 14, 15]. To this end, plastometric tests for the steel grade tested were used in the range of strain 0 – 1.3, strain rate 0.1 – 100 s^{-1}, and temperature 900 – 1100°C. The tests were performed in the Gleeble 3800 simulator. The yield stress (σ_p) as dependent on the rolling process parameters was determined by hot compression tests.

The plastometric tests were planned such as to enable the yield stress function and its coefficients to be determined based on the obtained plastic flow curves [15].

For the description of yield stress variation for BSt500S steel, function (1) was taken. This relationship is often used for the determination of the value of σ_p in software applications designed for numerical modelling of plastic working processes.

$$\sigma_p = K \cdot \exp^{m_1 \cdot T} \cdot T^{m_9} \cdot \varepsilon^{m_2} \cdot \exp^{\frac{m_4}{\varepsilon}} \cdot (1+\varepsilon)^{m_5 \cdot T} \cdot \exp^{m_7 \cdot \varepsilon} \cdot \dot{\varepsilon}^{m_3} \cdot \dot{\varepsilon}^{m_8 \cdot T} \qquad (1)$$

TABLE 2

Parameters of function (1) for the BSt500S steel

K	m_1	m_2	m_3	m_4	m_5	m_7	m_8	m_9
$1.78 \cdot 10^{-05}$	$-4.87 \cdot 10^{-03}$	0.180758	-0.27971	-0.007881	-0.0044	2.049118	0.000429	3.070798

where: σ_p – yield stress, T – temperature, ε – true strain,$\dot{\varepsilon}$ – strain rate, K, $m_1 m_9$ – coefficients of function [7].

After the approximation of plastometric test results, the coefficients of function (1) were determined. The values of these coefficients are given in Table 2.

The tests in the Gleeble 3800 simulator were planned so that the yield stress function and its coefficients could be developed for deformation process conditions during the hot rolling of ribbed bars with longitudinal band slitting. Examples of graphs of the relationship of yield stress versus actual strain for variable temperature and strain rate are shown in Fig. 3.

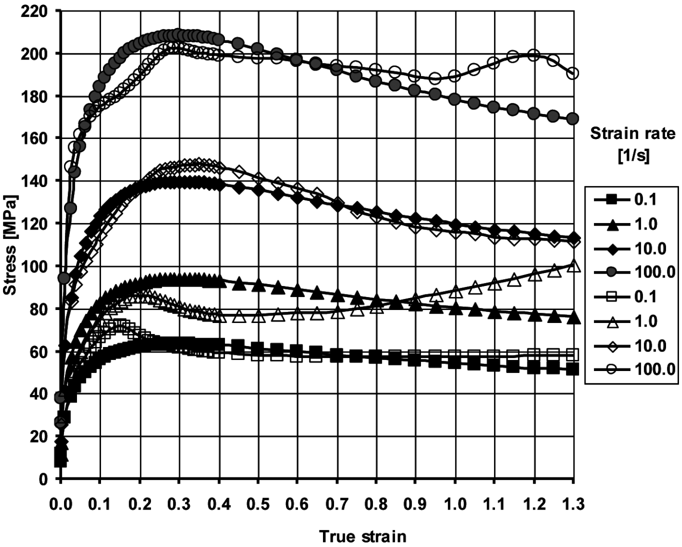


Fig. 3. Curves of BSt500S steel flow at a temperature of 1100°C; empty symbols – data from plastometric tests; blackened symbols – results from approximation acc. to function (1)

The numerical modelling of the 16 mm-diameter ribbed bar three-strand rolling process was conducted at an average band temperature of 1000°C [3, 4]. According to the data recorded during the actual rolling process, the following were taken for the computer simulation: tool temperature, 60°C; ambient temperature, 20°C; friction coefficient, 0.3; rolling speed, 6.5 m/s; roll diameter, 370 mm; the coefficient of heat exchange between the material and the tool, α_{tool} = 3000 [W/(K·m^2)]; and the coefficient of heat exchange between the material and the air, α_{air} = 100 [W/(K·m^2)], [7].

4. Mathematical wear models used in numerical modelling

For carrying out computer simulation of ribbed bar rolling using the multi-strand technology, the Forge2011® was used, which is a software application that uses the finite element method for solution. The computer simulations assumed the viscoplastic deformed metal model and the triaxial strain state, in which the mechanical state of the deformed material was described with the Norton-Hoff law [7-9]. The employed software program allows also the qualitative analysis of the wear of tools used in various plastic working processes to be made.

Determining the roll wear in a rolling process is extremely complex due to the dynamics of phenomena occurring in the roll gap. In the regions of contact between the metal and the rolls, the abrasive wear phenomenon occurs, which results from different friction conditions prevailing there, which are characteristic of the rolling process. The variable thermal conditions (high rolled band temperature) on the roll perimeter contribute to the erosion of the roll surface. It should be noted that during the operation of the roll, at its high rotational speed, the loads on the roll surface are of the impact type, which may contribute to faster roll wearing. One of the many models used for determining the abrasive wear is the Archard model, with the use of which the work of unit friction forces can be determined [10]. It is assumed in this model that, under the conditions of material abrasive wear, V_z , as related to the unit tool surface, it is directly proportional to the normal stress σ_n acting upon the tool surface and to the friction path, L_t, while inversely proportional to the hardness H of the material that undergoes wearing (in this case the tool hardness). This model can be written in the following form (2):

$$V_z = k_w \frac{\sigma_n L_t}{H} \tag{2}$$

where: k_w – wear coefficient.

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

$$V_z = k_w \int_0^t \frac{\sigma_n v_s}{H(T)} dt \tag{3}$$

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 [7-9].

For solving Eq. (3), the value of the wear coefficient, k_w, and the tool hardness, H, must be known [11-15]. 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 empirical data and determining the empirical coefficients in Eq. (3). Neglecting the effect of the wear coefficient $k_w$and the effect of temperature on the tool hardness allows Eq. (3) to be used for comparison purposes only. Therefore, in the model employed in the Forge2011® program, Eq. (4) has been simplified to the following form:

$$V_z = \int_0^t \sigma_n v_s dt \tag{4}$$

The wear model implemented in the Forge2011® 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 [7]. To be able to quantitatively determine the wear of the tools, Eq. (4) should be transformed to the following form:

$$V_z = \frac{k_w}{HV} \int_0^t \sigma_n v_s dt \tag{5}$$

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.

The determination of the quantitative roll wear is possible by taking into account the wear coefficient, which is related to physical parameters. The wear coefficient k_w is the unit mass loss as related to the surface area of contact with the tools and the length of the roll gap. In this study, Eq. (6) has been proposed for determining the wear coefficient.

$$k_w = \frac{\Delta V}{n_{obr} \cdot l_d \cdot A_{ld}} \tag{6}$$

where: n_{obr} – number of roll rotations during band rolling, l_d– roll gap length, A_{ld} – metal-to-roll contact surface area.

The wear coefficient k_w has a very significant effect on the quantitative roll wear. Its value may lie in a fairly large range for different processes, and is dependent both on the process and on the properties of the mating materials [10, 11, 16]. The value of the wear coefficient was determined based on the methodology provided in studies.

5. Theoretical and experimental examinations of the slitting pass rolling process

The correct determination of the unit friction force work involves many engineering parameters that must be determined. For this reason, numerical modelling of rolling the band from Stand 1 up to Stand 16 was carried out. Variations in band cross-section temperature were allowed for in the computer simulations by passing the band temperature distribution on to the next rolling passes. Simulation of band cooling between rolling passes according to the durations of breaks between individual rolling stands resulting from the appropriate rolling speed was also performed. In ribbed bar hot rolling, the process of recrystallization occurs between successive deformations, which should be considered in computer simulations by removing the deformation history after respective rolling passes. The investigation carried out determined the parameters necessary for determining the slitting pass wear. For determining the wear of the slitting passes, the results of unit roll friction force work computation done using the Forge2011® software program were used.

To make use of the results of simulation using the simplified Archard model for quantitative roll wear evaluation, it is necessary to define the wear coefficient. Based on the performed computer simulation it was possible to determine the distribution of unit friction force work over the roll surface. Figure 4 shows the obtained values of unit friction force work across the width of the pre-slitting pass (Stand 15) and the slitting pass (Stand 16). These values are the means obtained for three measurement lines after band exit from the roll gap.

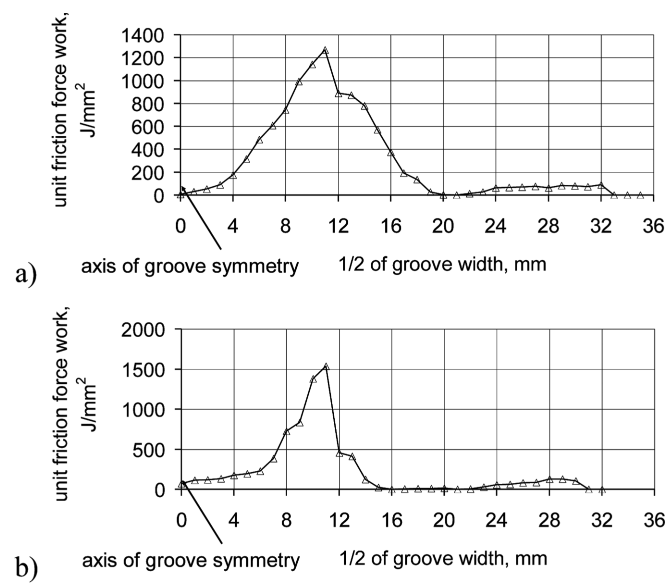
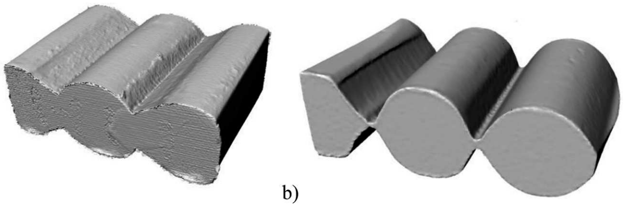


Fig. 4. Distribution of unit friction force work on surface of rolls: a) Stand 15 – pre-slitting groove, b) Stand 16 – slitting groove

From the results of the theoretical examinations it can be found that during band rolling in the pre-slitting pass (Stand 15) and the slitting pass (Stand 16) the highest unit friction force work values occur in the knife parts of the pass, where bridges connecting individual band strands are created, and they decrease with increasing distance from the axis of symmetry of the pass. The bar rolling computer simulations for pre-slitting pass rolling yielded a unit friction force work value of approx. 1260 J/mm^2, while for slitting pass rolling, a value of 1530 J/mm^2, that is greater by 21%. These values occurred in the knife parts of the slitting passes under examination.

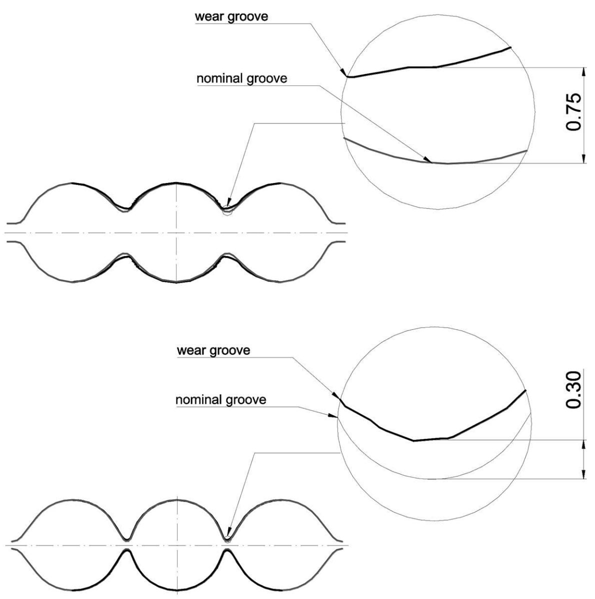
The next stage of the study was to carry out of experimental tests which would determine the change in the shape of the slitting passes after a rolling campaign. These tests involved the mapping of the shape of the worn passes by rolling aluminium templates after a specific mass of bars had been rolled. Next, these specimens were scanned with a 3D scanner and then three cross-sections of each of them were made in a CAD program with the aim of taking the measurement of their shape (Fig. 5).



a) b)

Fig. 5. Models of aluminium templates obtained by scanning 3D imitating the shape of the used slitting passes: a) sample after rolling in Stand 15 – pre-slitting pass, b) sample after rolling in Stand 16 – slitting pass

The determined cross-sections of the scanned specimens enabled the determination of the variations in the dimensions of the passes as against the nominal passes. Figures 5a and 6a represent the shape of a pre-slitting pass after 1770 Mg of bars have been rolled, while Figures 5b and 6b show the shape of a slitting pass after rolling 980 Mg of bars. In the experimental tests carried out under industrial conditions, the mass of steel rolled in the pre-slitting passes is, on average, two times the mass of material rolled in the slitting pass. The reason for the frequent change of the slitting pass is the need for maintaining the correct heights of bridges joining the individual strands of the rolled band, whose nominal height was 0.9 mm. As the rolls are operated and the pass combs wear out, the bridges between the strands increase in thickness. Correcting this dimension in industrial conditions is done by reducing the gap between the rolls. However, such a modification results in decreasing the surface area of the cross-section of individual strands and ultimately makes the further rolling impossible (due to failing to meet the dimensional tolerance of the finished product). In the case of pre-slitting pass rolling, the wear of the combs is smaller on account of their larger rounding radii, hence, in spite of the comb wear, the pre-slitting pass may remain in service longer compared to the slitting pass.



a)

b)

Fig. 6. Shape of passes obtained during rolling process in experimental examinations compared to the nominal shapes of passes:
a) pre-slitting pass, b) slitting pass

The analysis of the shape of worn slitting passes found that their greatest wear occurs also in the location of the pass combs that separate the band (Fig. 6). The obtained aluminium template shape measurement results confirmed the results of numerical modelling of rolling in the slitting passes, where the unit friction force work on the comb surfaces is the greatest. The average comb loss of the pre-slitting pass amounted to 0.75 mm, while that of the slitting pass, 0.3 mm. The greater wear of the pre-slitting pass (Fig. 6a) is the results of a larger bar mass (1770 Mg) that has been rolled.

The theoretical and experimental examinations carried out provided the necessary information on the unit work of friction forces and the actual wear of the slitting passes. Thanks to this information it was possible to determine the quantitative roll wear.

The loss of the pass volume (pass wear) was determined based on the measurement of the geometry of aluminum templates rolled, which were used for the experimental tests. Using those templates, the pass shape at the beginning and end of the rolling campaign was mapped. The change in the band cross-section shape and the roll volume loss were determined in a CAD program. The loss of volume ΔV in Stand 15 after rolling 1770 Mg of finished product was 1658.56 mm^3, while in Stand 16 after 980 Mg of finished product had been rolled, it amounted to 588.02 mm^3. The obtained data allowed the determination of the wear coefficient, k_w, from relationship (6): The remaining data required for Eq. (6) are as follows:

- n_{obr} for rolling 1770 Mg bars – 218 546.71 rotations,

n_{obr} for rolling 980 Mg bars – 119 302.88 rotations,

- l_d in Stand 15 (pre-slitting pass) – 46.70 mm,

l_d in Stand 16 (slitting pass) – 37.12 mm,

- A_{ld} in Stand 15 (pre-slitting pass) – 101.57 mm^2,

A_{ld} in Stand 16 (slitting pass) – 108.09 mm^2.

By substituting the obtained data in Eq. (6), the wear coefficient k_w was calculated, whose value for the pre-slitting pass amounted to $1.59 \cdot 10^{-6}$, while for the slitting pass, $1.22 \cdot 10^{-6}$. The obtained wear coefficient values differ slightly, which results from inaccuracies in the measurement of the worn slitting passes. The main problem is the method of measuring the band cross-section. For further calculations, the average wear coefficient value was taken, which is $1.4 \cdot 10^{-6}$.

The calculated value of the wear coefficient k_w was then used for determining the quantitative slitting pass wear using Eq. (5). By substituting the obtained unit friction force work values determined from numerical modelling, and the roll hardness and the roll wear coefficient, the theoretical shapes of the pre-slitting and slitting pass grooves were determined after 1000 Mg of bars had been rolled (Fig. 7).

Based on the developed methodology for determining the quantitative roll wear, the wear after rolling 1000 Mg of bars was calculated. The calculation results are represented in Figure 7. The wear of the passes in the comb location was, respectively, 0.43 mm for the pre-slitting pass and 0.47 mm for the slitting pass. The higher value of the calculated slitting pass wear as against the actual wear is due to the use of the average wear coefficient value for both passes. The actual wear coefficient for this pass was smaller than the wear coefficient determined for the pre-slitting pass, hence the calculated wear value is greater.

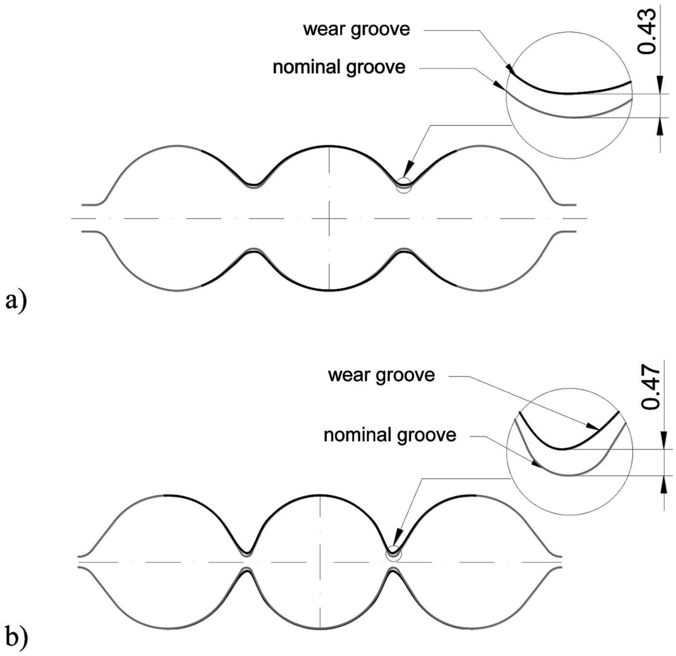


Fig. 7. Theoretical shape of pre-slitting pass and slitting pass after rolling of 1000 Mg bars compared to nominal shape of the passes: a) pre-slitting pass, b) slitting pass

The main focus in the study was on the pass combs, whose wear in the ribbed bar rolling process is definitely greater compared to the wear of the groove bottom of the pre-slitting and slitting passes. The developed methodology enables the wear of slitting passes in the multi-strand ribbed bar rolling process to be determined with satisfactory accuracy.

6. Summary

Theoretical and experimental examinations of the roll wear in the process of ribbed bar rolling using multi-strand technology have been carried out within the study. At the same time, the study has been limited to determining the wear of slitting passes that, in the rolling process, prepare the band for being split on separating rollers. The wear of these passes is the greatest and affects the stability of the conducted rolling process. Based on the obtained results it is possible to determine the wear of passes and their service life, which may partially reduce the breaks in Rolling Mill operation resulting from failures occurred due to the excessive wear of the slitting passes. Predicting the roll wear might reduce the quantity of faulty products resulting from the incorrect pass geometry.

Further investigations will enable the roll wear coefficient values to be systematized and a model to be developed, whose job will be to predict the wear of passes for any arbitrary pass shape in a rolling line.

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