Arch. Metall. Mater., Vol. 61 (2016), No 1, p. 183–188

DOI: 10.1515/amm-2016-0032

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THEORETICAL ANALYSIS OF THE INFLUENCE OF LONGITUDINAL STRESS CHANGES ON BAND DIMENSIONS DURING CONTINUOUS ROLLING PROCESS

The paper presents the results of studies on the effect of nonuniform temperature distribution over the length of feedstock on the variation of longitudinal stresses in the rolling direction and band dimension change during the continuous rolling process. The studies were performed based on actual engineering data for a 160x160 mm square cross-section feedstock of steel S355J0. Numerical modelling of the rolling process was performed using Forge 2008®, a finite-element based computer program. Thermovision measurements and bars geometrical dimension changes were carried out in a domestic steelworks.

Keywords: continuous rolling process in grooves, nonuniform temperature distribution, tension and concentration of band, FEM

1. Introduction

While carrying out the continuous rolling process in grooves, the factors that may affect the law of constant volume metal disturbance must be controlled. One of these factors is the temperature change along the length of the rolled feedstock. Nonuniform temperature distribution along the length of rolling feedstock greatly affects the changing conditions of plastic metal flow in the roll gap during the continuous rolling process. The temperature variation across the rolled feedstock length directly influences friction conditions and the plastic properties of the metal being rolled, and thereby on the forward slip and band widening during the continuous bar rolling process. The change of these parameters in the case of the continuous rolling process causes a change in the values of longitudinal stresses in the band rolling directions between the adjacent rolling stands [1-5].

The main cause of the occurrence of nonuniform temperature distribution over the feedstock length is the heating process in a furnace [6]. Feedstock heating prior to the plastic working processes is done in heat furnaces of different designs. In the case of shape mills, either walking beam or pusher furnaces are widely used. The operation and feedstock heating regime of these furnaces allow the continuous operation of the rolling mill without having to introduce breaks for charge loading and unloading [7-11].

The computer program Forge 2008® [12-14] was used in this study for numerical modelling of the rolling process. The band flow was modelled taking into account the nonuniform temperature distribution over its length.

2. Methodology and conditions adopted for research

Experimental studies were carried out on the technological conditions of one of the bar rolling mills D 370. A thermovision camera, ThermaCAM SC640 FLIR Systems, was used for research. During the thermal tests, the following object parameters were used: emissivity of 0.82, distance of the object from the camera 3 m, ambient temperature 20°C, deflected 20°C, relative humidity 50%. ThermaCAM Researcher Professional software was used for processing the results of the measurements. The material used for the study was feedstock from steel S355J0, with a length of 12 m and a square cross-section of the side of 160 mm, heated in a walking beam furnace to a temperature of 1160°C. This steel is classified as a non-alloy structural steel. The applied steel grade is most often used for small structures responsible for general construction and industry. Elements that are made from this type of steel can be joined by welding, riveting and bolting. Unalloyed structural steels after hot rolling process are provided in the form of long, flat products (sheets, strips, bars, profiles). The basis for the classification of these steels are the mechanical properties with chemical composition being an additional criterion for acceptance (Polish Standard PN-EN 10025, 2002). The chemical composition and mechanical properties of the test steels shown in Tables 1 and 2.

TABLE 1
The chemical composition of the hot- rolled non-alloy structural steel S355J0 according to PN-EN 10025:2002

Grade of steel	The maximum content by weight of elements, %					
	C	Mn	Si	P	S	N
S355J0	0.22	1.6	0.55	0.04	0.04	0.009

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TABLE 2
Selected mechanical properties of hot-rolled structural steel S355J0 according to PN-EN 10025:2002

Grade of steel	The minimum mechanical properties		
	R_{eH} [1], *MPa*	R_m [2], *MPa*	A [3], %
S355J0	355	490	22

1) ÷ 3) Samples longitudinal from products with a thickness: 1) ≤ 16 mm, 2) 3 ÷ 100 mm, 3) 3 ÷ 40 mm.

For the numerical studies, engineering data for the round bars of 70 mm in diameter rolling process in the D370 shape mill was used. During the numerical modeling of a continuous rolling process three variants of the feedstock from steel S355J0 were adopted. The first variant of the feedstock with a cross section of 160x160 mm and a length of 300 mm and initial temperature of 1150°C. The second variant of the feedstock with a cross section of 160x160 mm and a length of 300 mm and initial temperature of 1060°C. The third variant, feedstock with a cross section of 160x160 mm and a length of 2000 mm, along its length nonuniform temperature distribution was introduced, the difference of which being 90°C (Fig. 1).

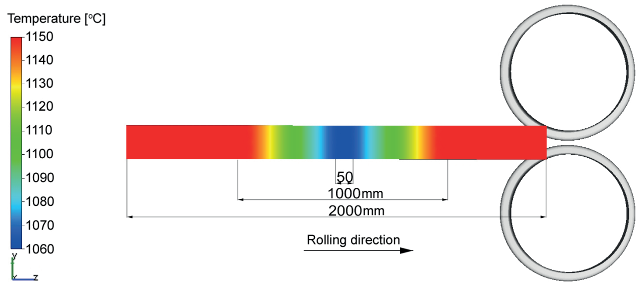

Fig. 1. The initial temperature distribution over the feedstock length used for numerical simulations of rolling process of round bars of 70 mm in diameter

For the friction coefficient, values from 0.35 at a temperature of 1200°C to 0.5 at 800°C were assumed, while the friction factor values were taken based on the results provided in work [1, 2, 16], which ranged from 0.6 at 1200°C to 0.9 at 800°C. The temperature of the rolls was 60°C, while ambient temperature was taken as 20°C. The coefficient of heat exchange between the rolls and the band was α = 3000 W/m^{2}K; the coefficient of heat exchange between the band and the air, α_{air} = 100 W/m^{2}K; thermal conductivity - 35.5 W/(m·K); specific heat - 778 J/(kg·K); emissivity - 0.82. The data used in numerical modelling have been verified successfully in the analysed industrial mill [10].

3. The experimental results

The result obtained from study show a nonuniform temperature distribution along the feedstock length after heating in a walking beam furnace (Fig. 2).

The results of thermovision measurements have identified nonuniform temperature distribution along the feedstock length. The differences between the temperature change in the range of about 50 – 110°C (Fig. 2). The nonuniform temperature distribution along the feedstock length in the analysed rolling mill, is due to the existence of areas with a lower heating temperature in the furnace chamber. Areas with lower temperatures during the feedstock heating process are usually set in the seals contact place with fixed and moving beams of the walking beam furnace hearth (Fig. 3).

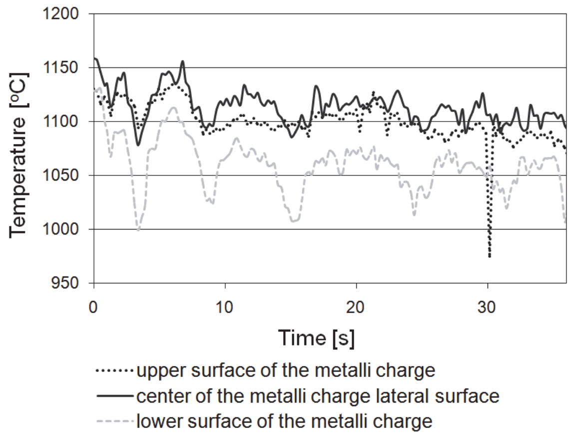

Fig. 2. Temperature change on the feedstock length after the heating process in a walking beam furnace

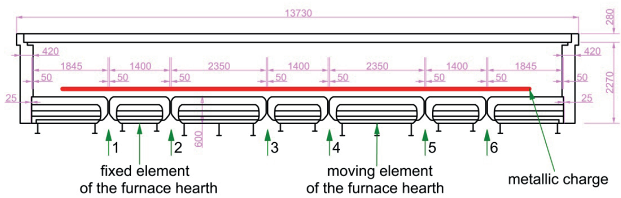

Fig. 3. Schema of walking beam furnace, the cross section

In the examined walking beam furnace, there are six zones (the places shown in Fig. 3 by arrows 1÷6), where the furnace heating chamber gets cold air. This phenomenon is caused by abrasion to the furnace seals during operation which caused the occurrence of scale in this area, which then drops out from the feedstock during the heating process. As a result of the rolling process with round bars of 70 mm in diameter, the feedstock length of 12 m yielded a finished product with a total length of 66 m. The band was cut into 11 sections with a length of 6 m each. Geometric studies (height and width) of the bars length were made from a single band divided into commercial lengths. Figure 4 shows the geometrical dimensions obtained for the finished bars.

The measurements of height and width of the round bar over the length showed the significance of nonuniform temperature distribution on the feedstock in changing the geometrical dimensions of the finished round bars. For round bars of 70 mm in a diameter, in accordance with the standard [15], dimensional tolerance is ± 1.0 mm. The obtained experimental results (Fig. 4) are found to exceed the positive tolerances of the round bar over its length. Dimensions incompatible with the requirements of tolerance were observed between 28 ÷ 31 m, 40 m, 47 ÷ 50 m, 56 to 60 meters length of the finished band. The positive tolerances were exceeded by about 30 % of their value. The minimum diameter of the round bar was 69.13 mm and the maximum diameter was 71.29 mm.

Analyzing the results of measurements (Fig. 4) also have been found that the change in the geometric dimensions of the round bar is dependent on nonuniform temperature distribution along the feedstock length (Fig. 2).

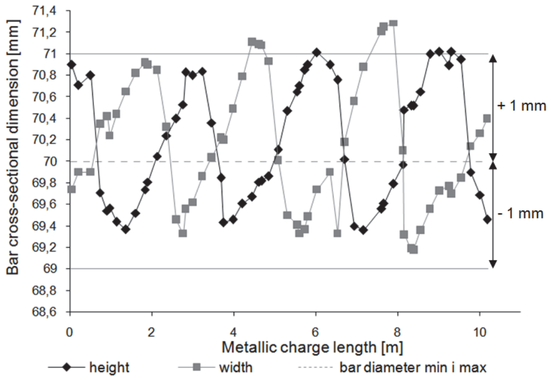

Fig. 4. Changing the geometrical dimensions of the round bar 70 mm in diameter rolled from a feedstock with a nonuniform temperature distribution over its length

4. Results of theoretical research

In the first stage of the theoretical research, numerical modelling of rolling process was performed on round bars of 70 mm in diameter from an initial feedstock with a constant temperature (variant I - 1150°C, variant II - 1060°C). Feedstock and roll bands were obtained at the same time in a single pass.

On the basis of the numerical simulations of round bars rolling process results from feedstock, with the initial temperature 1150°C (variant I) and 1060°C (variant II) cross-sections of bands were performed after each pass (Fig. 5). The cross-sections were performed in the plane of the output bandwidth of the roll gap. Analyzing the bands dimensions after individual passes for rolled bars according to two variants found that the temperature change of the initial feedstock did not affect the band height but has a significant impact on the bandwidth. The obtained bands height rolled by both methods were the same, in accordance with the height of the groove used in the numerical modeling of rolling bars of 70 mm in diameter. During the band rolling process from feedstock with a higher initial temperature (variant I), a round bar with a width of 70.90 mm was obtained. Whereas, during the band rolling process from feedstock with a lower initial temperature (variant II), a round bar with a width of 70.71 mm was obtained. The initial temperature difference, which was 90 °C, resulted in an obtained difference of about 0.19 mm in the width of the finished bars. When comparing the geometric dimensions and shape of the cross section of bands obtained after individual passes for both variants, the greatest differences observed were in bandwidth ranging from 0.83 mm in stand No. 4 to 1.20 mm in stand No. 1, obtained in passes 1, 3, 4. However, after passes No. 2 and 5 the differences in bandwidth for both variants were respectively 0.31 and 0.39 mm. In the case of passages No. 6 and 8, these differences were respectively 0.18 and 0.19 mm, but in this case bands derived from a feedstock with higher initial temperatures have a higher width than the band rolled from feedstock with the lower initial temperature. Data presented in Figure 5 shows that the bands dimensions after pass 7 are the same. This was due to higher widening of the rolled band according to variant I, then rolled band according to variant II.

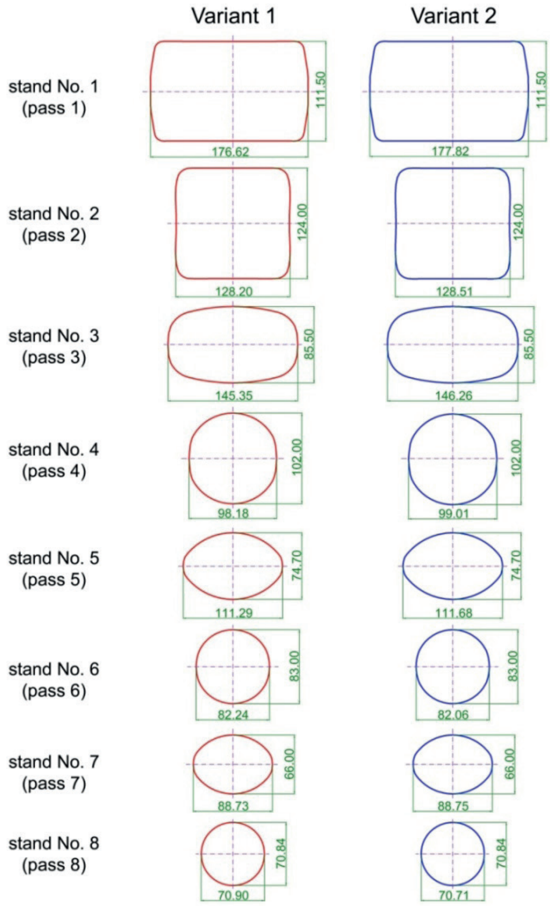

Fig. 5. The shape and dimensions of bands cross sections obtained during the numerical simulation of rolling process of the round bars of 70 mm in diameter from feedstock with an initial temperature of 1150 °C (variant I), and 1060 °C (variant II)

When analysing the changes in the width and band extension after individual passes, obtained by numerical simulation of the round bars rolling process from feedstock with initial temperature of 1150°C and 1060°C, it was found that in addition to the feedstock temperature, the metal plastic flow in the grooves is also affected by the value of inflicted deformation. Figure 6 shows the calculated values of the band extension obtained by numerical simulation of the feedstock rolling process according to variant I and II.

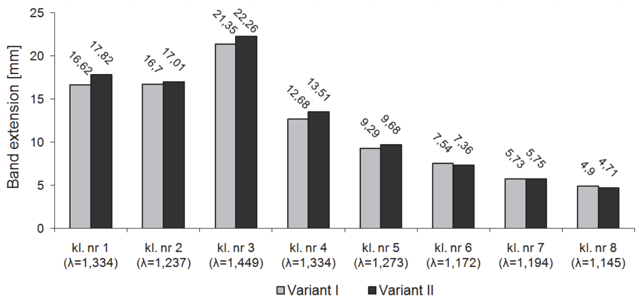

Fig. 6. Changes in the band elongation obtained during the numerical simulations of rolling process of the round bars of 70 mm in diameter from feedstock with different initial temperatures

By analysing the data shown in Fig. 6, it can be concluded that the average value of the applied elongation factor (Fig. 6, the values given in brackets) during the rolling process results in band extension. Application of an elongation factor higher than 1.2, with the concomitant decrease in band temperature causes an increase in its expansion value. However, using the coefficients elongation of less than 1.2, while reducing feedstock initial temperature causes the band extension to decrease. In the case of bands rolled in mill stand No. 7, which uses the coefficient value elongation of 1,194 difference in the rolled bands extension according to variant I and II was 0.02 mm. This was due to the fact that the rolled band according to variant I before passing in a rolling mill No. 7 was larger in width than the band rolled in variant II.

Changes in temperature and band extension has also changed the band plastic flow velocity received in the rolling direction (Fig. 7).

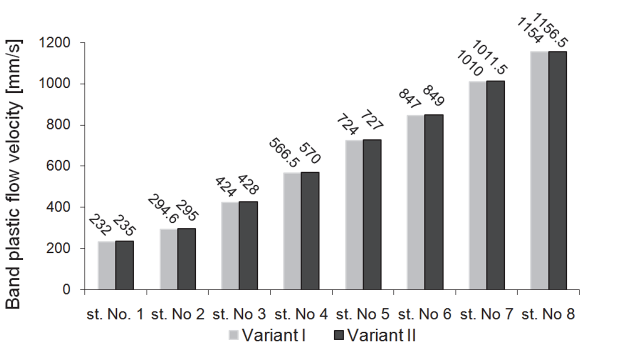

Fig. 7. Band plastic flow velocity changes obtained during numerical simulation of the continuous rolling process of the round bars of 70 mm in diameter from feedstock according to variant I and II

Analysis of the band plastic flow velocity variation in the rolling direction in the stands No. 1 ÷ 8 has been found that the feedstock initial temperature influences its change. During the numerical simulation of the continuous rolling process of the round bars of 70 mm in diameter higher band plastic flow velocity in rolling direction was obtained for variant II. The feedstock initial temperature change from 1150°C (Variant I) to 1060° C (variant II) caused an increase in friction in a the roll gap, which increased band forward slip value. Adoption of initial temperature difference of 90°C for different feedstocks (variant I and II) has increased the band plastic flow velocity value for variant II from about 0.2 % to 1.3 % relative to the values obtained band plastic flow velocity for variant I. During the continuous bars rolling process, it must be noted that there are no differences in the initial temperature between successive feedstock, because it disturbs the constant volume law of metal through the roll gap during the rolling process, which may lead to changes in value of band tension and concentration. Changing band plastic flow velocity value is also dependent on the coefficients of elongation during the band rolling process in the following passes. The greatest increases in band plastic flow velocity value was observed in passes 1, 3 and 4, in which the elongation values were higher than 1.3.

The next step of theoretical research was numerical simulation of the continuous rolling process of round bars of 70 mm in diameter from the feedstock with nonuniform temperature distribution along its length (Fig. 1). For this purpose feedstock and the obtained band was rolled at the same time at least two passes. After the numerical simulation of the continuous rolling process of round bars of 70 mm in diameter from the feedstock with a nonuniform temperature distribution along the bands length the cross-sections were performed after each pass (Fig. 8). Cross-sections performed for the areas of band with a higher (Fig. 8a) and lower (Fig. 8b) initial temperature. These cross sections, as with the bars rolling process from feedstock with different initial temperatures, were taken in the plane of the band output from the roll gap. Analysis of the band shape and dimensions after individual passes found that the temperature change in the volume of feedstock affects the results of band extent. During the band rolling process from feedstock with a nonuniform temperature distribution along the length, round bars with variable dimensions along their length were obtained. For band areas with a higher initial temperature dimensions of the finished bar were 71.11 x 70.84 mm, while for the band areas with a lower initial temperature the finished dimensions of the bar were 70.31 x 70.84 mm. Implementation of the initial temperature difference along the feedstock length, which was 90°C (Fig. 1) caused a difference in the width of 0.80 mm on the final bar length, for the areas of higher and lower temperature (stand No. 8, Fig. 8). Having compared the shape and dimensions of the band cross section after individual passes for the areas of higher and lower temperatures, it can be concluded that the greatest differences in the bandwidth were obtained after the stands No. 1, 3, 4, 5 (for example, 2.48 mm for stand 1 and 1.32 mm for stand No. 5, Fig. 8). After rolling mill No. 2 differences in bandwidth for the areas of higher and lower temperature decreased to 0.30 mm. However, for bands obtained after rolling stands No. 6, 7 and 8, the differences in bandwidth were respectively 0.45, 0.18 and 0.80 mm. It should be noted that for these passes band areas of higher temperature have a higher width than the band areas of lower temperature. The recorded band changes after individual passes (Fig. 8) were also dependent on the applied elongation factor, as in bars rolling process from feedstock with different initial temperature (Fig. 5). During rolling process of band areas with a lower temperature and elongation coefficient larger than 1.2 higher bandwidth than for the band areas with higher temperature was observed, which is consistent with the work [3, 6]. However, during rolling process of band areas with a lower temperature and elongation coefficient less than 1.2 a smaller bandwidth was observed.

Based on the results of the bars rolling process from the feedstock with initial temperature of 1150 °C and 1060 °C (Fig. 5) and a continuous bars rolling process from the feedstock with a nonuniform temperature distribution over its length (Fig. 8) have found that a high influence on the band dimensions change has a way of modelling the rolling process. Modelling of the rolling bars process with different initial temperatures, gives lower bandwidth values (Fig. 5) than the modelling of continuous rolling bars with nonuniform temperature distribution along the length (Fig. 8). In the first and second variant, bands were rolled at the same time only in one pass, which in turn eliminated the possibility of including band tension or band loop that occur during the continuous rolling process (variant III). The main cause of the differences in bandwidth over the length is the disturbance of steady rolling process caused by temperature changes in the rolled band volume. Analysing the theoretical study results of the impact of the feedstock initial temperature on the band plastic flow velocity change (Fig. 7) showed that the growing change in the band plastic flow velocity during continuous rolling process affects the bandwidth. During the continuous bars rolling process from the feedstock with nonuniform temperature distribution along its length in stand mill No. 1 ÷ 8, there are band areas between rolling stands, in which longitudinal stress (tensile or compressive) are formed in the rolling direction. In order to accurately determine the impact of nonuniform temperature distribution along the band length during the rolling of its regions with higher and lower temperature in the two adjacent rolling stands, a longitudinal stress distribution analysis was performed (in the rolling direction) during continuous rolling process. Figure 9 shows results of numerical calculation of the temperature distribution and longitudinal stresses during band rolling process in the stands mill No. 2 to 4 from a feedstock with nonuniform temperature distribution over its length.

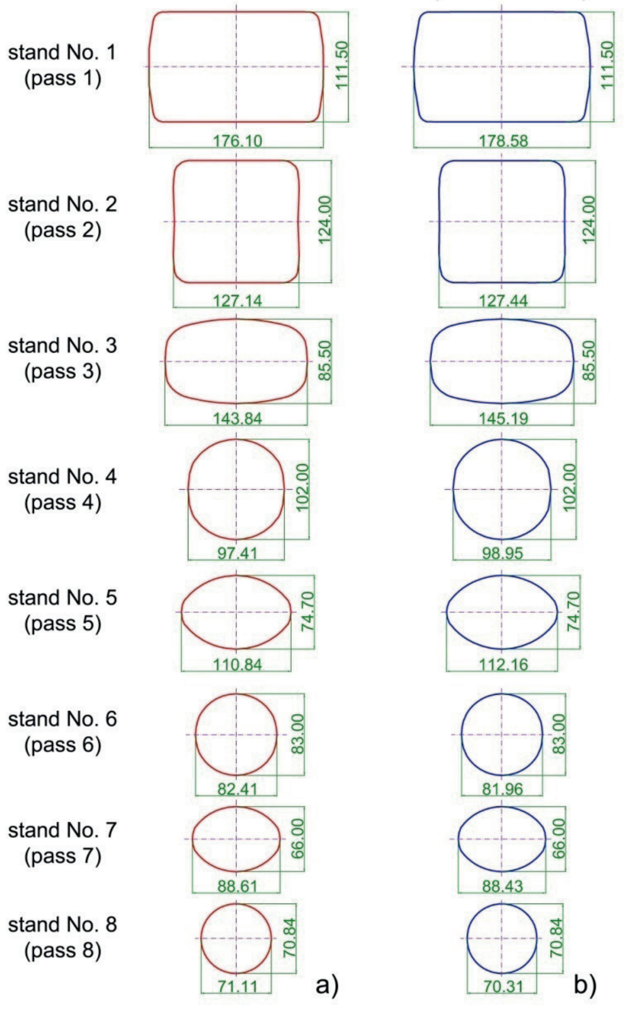

Fig. 8. The shape and dimensions of band cross sections obtained during the numerical simulation of the continuous rolling process of the round bars of 70 mm in diameter from the feedstock having a nonuniform temperature distribution: a) the band area with higher initial temperature, b) the band areas with lower initial temperature

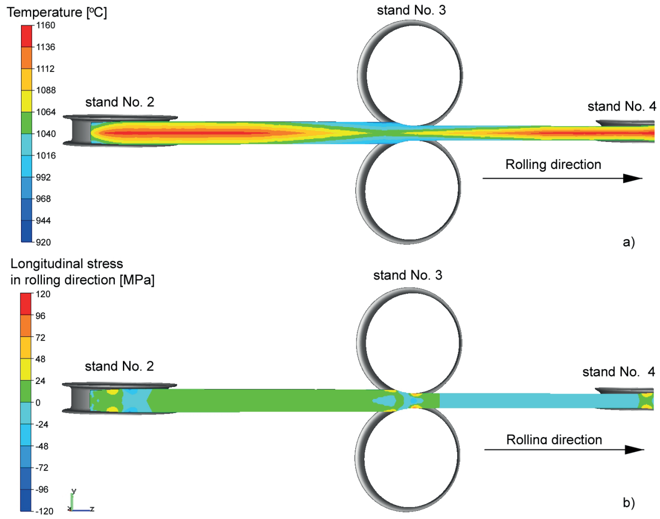

Fig. 9. The temperature distribution - a) and longitudinal stresses (in the rolling direction) - b) during the continuous bars rolling process in rolling stands No. 2 to 4 from a feedstock with nonuniform temperature distribution along the length

Analysing the results of the numerical simulation of the band rolling process in the stands No. 2 ÷ 4 (Fig. 9) it has been found that applying nonuniform temperature distribution along its length significantly affects the distribution of longitudinal stresses in the deformed band. During the band areas rolling at a lower temperature in the rolling mill stand No. 3 the band areas with a higher temperature there is an increase of band plastic flow velocity in the rolling direction after the band leaves roll stand No. 3, which in turn causes the appearance of additional longitudinal stresses in the rolled band between individual stands. On the band section between the stands No. 2 and 3a tension longitudinal stresses area in the rolling direction of the maximum values of around 3 MPa is formed, causing the tension of band between the stands. However, the band distance between rolling stands No. 3 and 4 forms an area of compressive stress in the longitudinal direction of rolling with a maximum value of about -1.5 MPa, causing the band loop between the stands. Based on the results presented in [1] and theoretical research results, the impact of changes in the value of longitudinal stresses (Fig. 9) to change the band extension it has been found that the resulting band tension or the concentration affects more the backward slip zone than the forward slip zone in the roll gap, leading to changes in the rolled band shape and dimensions (Fig. 8).

Figure 10 shows the changes in longitudinal stress values in the band between individual rolling stands during continuous rolling process of round bars of 70 mm in diameter from feedstock with a nonuniform temperature distribution along the length. During continuous rolling process of band areas with higher and lower temperatures between adjacent rolling stands band tension occurs (Fig. 10a), whereas during continuous rolling band areas of lower and the higher temperature between adjacent rolling stands for band loop occurs (Fig. 10b).

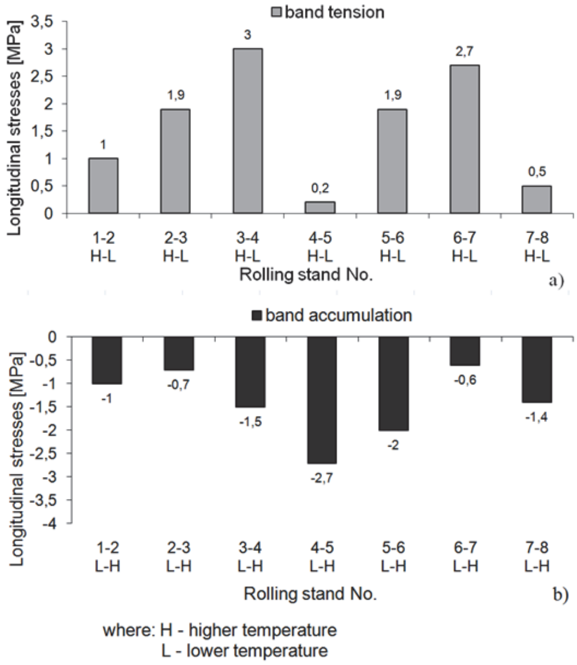

Fig. 10. Changes in the longitudinal stresses value in the band between individual stands during the continuous rolling process of round bars of 70 mm in diameter

From the data shown in Fig. 10, it follows that depending on the temperature of the band area rolled the largest differences in values between the bands tension and the loop occur after the stands from 3 to 6. This causes the longitudinal stresses occurring in the band between the rolling stands to vary from 1.9 to 4.5 MPa. Large differences between the band tension and loop value in the band between rolling stands No. 3 to 4 and 4 to 5 due to the fact the selection of too low a velocity rolling mill stand at No. 4 on velocity rolling in mill stand No. 3, and this in turn has led to compressive stresses in the band between mill stands No. 4 to 5 being higher.

5. Conclusion

On the basis of experimental and theoretical studies of continuous rolling process of round bars of 70 mm in diameter from feedstock with a nonuniform temperature distribution along its length, it can be concluded that during the band areas rolling with higher and lower temperatures in adjacent rolling stands there is the appearance of longitudinal stresses in the rolling direction. The biggest differences between the bands tension and concentration values occur after stands No. 3 to 6. In the case of numerical simulations of band rolling process from feedstock with different initial temperatures, the difference in width of the obtained bars was 0.19 mm, and in the case of numerical simulation of continuous bars rolling process from the feedstock with nonuniform temperature distribution, the resulting differences in the width of the areas of higher and lower temperatures were 0.80 mm. Performance of numerical modelling of band continuous rolling process should be rolled in at least two adjacent rolling stands, as it provides included rising tension and concentration in rolled band.

Received: 20 January 2015.

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