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NUMERICAL MODELING OF THE MICROSTRUCTURE DURING 50X20 MM FLAT BARS ROLLING PROCESS

NUMERYCZNE MODELOWANIE MIKROSTRUKTURY PODCZAS WALCOWANIA PRĘTÓW PŁASKICH 50X20 MM

In this work theoretical analysis of the microstructure change in the material during normalizing rolling of the 50x20 mm flat bars was presented. Theoretical analysis was made with computer program Forge 2007, based on the finite-element method. An analysis was made for two cases of accelerated cooling during rolling process. Based on the numerical results of 50x20 flat bars rolling process the average recrystallized austenite diameter and basic energy and force parameters. Proposed modification of the 50x20 mm flat bars rolling technology involving accelerated cooling, results in the reduction of average austenite diameter, which could cause improving strength of the final product.

Keywords: normalizing rolling, accelerated cooling, microstructure

W pracy przeprowadzono badania numeryczne, których celem było modelowanie zmian strukturalnych zachodzących w odkształcanym paśmie podczas walcowania nirmalizującego prętów płaskich 50x20 mm. Badania przeprowadzono przy użuciu programu komputerowego Forge 2007, umożliwiającego modelowanie zmian mikrostruktury. Rozważano dwa warianty przyspieszonego chłodzenia. Na podstawie przeprowadzonych badań procesu walcowania prętów płaskich 50x20 mm określono średnią wielkość zrekrystalizowanego ziarna austenitu oraz podstawowe parametry energhetyczno – siłowe. Zaproponowane midyfikacje technologii walcowania prętów płaskich 50x20 mm polegające na wprowadzeniu dodatkowego przyspieszenia chłodzenia wodnego walcowanego pasma w ciągu walcowniczym powodują zmniejszenie wielkości ziarna austenitu, co wpłynie na zwiększenie wutrzymałości gotowych wyrobów.

1. Introduction

Rolled products, and especially long products, constitute an important and significant part of the general production of steel products [1, 4, 7]. Present technologies for the rolling of plain round bars and flat bars in continuous shape mills are characterized by a very small difference between the feedstock temperature and the rolling end temperature which is approx. 1000°C. Due to this, the correct strength and plastic properties of finished products cannot be assured. In addition to its strength and plastic parameters, the applicability of a constructional material is determined especially by its impact resistance (or, more often, breaking energy in J) that is determined at ambient or lower temperatures of -20°C – -60°C, depending on the conditions of application. A parameter particularly influencing the magnitude of impact toughness energy, as well as the behavior of steel passing into a brittle state, is the grain size of the material and its inhomogeneity.

2. The mathematical model implemented in the Forge 2007 program

For modeling of the three-dimensional plastic flow of metal during rolling 50x20mm flat bars, a finite element method-based computer program, Forge 2007, was employed, in which the mechanical state of material being deformed is described with the Norton-Hoff law [2]:

$$S_{ij} = 2K_0(\varepsilon + \varepsilon_0)^{n_0} \cdot e^{(-\beta_0 \cdot T)}(\sqrt{3}\dot{\varepsilon})^{m_0-1}\dot{\varepsilon}_{ij} \qquad (1)$$

where: S_{ij} – stress tensor deviator, $\dot{\varepsilon}$ – strain rate intensity, $\dot{\varepsilon}_{ij}$ – strain rate tensor, ε – strain intensity, ε_0 – initial strain, T – temperature, K_0, m_0, n_0, β_0 – material constants related to the characteristic properties of a given material.

The friction conditions on the surface of metal-rolls contact are described with the Coulomb friction model and the Treska friction model, in which appropriate coefficient values are taken:

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$$\tau_j = \mu \cdot \sigma_n \quad \text{dla} \quad \mu \cdot \sigma_n < \frac{\sigma_0}{\sqrt{3}} \tag{2}$$

$$\tau_j = m\frac{\sigma_0}{\sqrt{3}} \quad \text{dla} \quad \mu \cdot \sigma_n > m\frac{\sigma_0}{\sqrt{3}} \tag{3}$$

where: τ_j – friction stress, σ_0 – initial stress, σ_n – normal stress, μ – friction coefficient,
m – friction factor.

For the determination of the temperature field, a differential equation is used, which describes variations in temperature for transient heat flow. This is a quasi-harmonic equation that can be expressed in the following form:

$$\frac{\partial}{\partial x}\left(k_x\frac{\partial T_s}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_y\frac{\partial T_s}{\partial y}\right)+\frac{\partial}{\partial z}\left(k_z\frac{\partial T_z}{\partial z}\right)+\left(Q - c_p\rho\frac{\partial T_s}{\partial t}\right) = 0 \tag{4}$$

In the above equation, k_x, k_y and k_z are the functions of distribution of thermal conductivity coefficients in the directions x, y, z. The T_s is a function used to describe temperature in the zone under consideration. The Q is the function of distribution of deformation heat generation rate, the c_p is the function of distribution of metal specific heat, and the ρ is the function of distribution of metal density. For the boundary conditions, the combined limiting conditions of the second and third kinds were adopted, which can be written in the form below:

$$k_x\frac{\partial T_s}{\partial x}l_x + k_y\frac{\partial T_s}{\partial y}l_y + k_z\frac{\partial T_s}{\partial z}l_z + q + \alpha_k(T_s - T_{ot}) = 0 \tag{5}$$

In the above equation, l_x, l_y i l_z are the directional cosines of the normal to the strip surface, q is the intensity of heat flow over the cooled zone surface, and $\alpha \cdot_k$ represents convective losses. Equation (4) and boundary condition (5) uniquely define the heat exchange during modelling of the rolling process.

For simulation of the grain size distributions of statically recrystallized austenite, the Recrystallization module of the Forge2007® program was used. The Recrystallization module makes use of the following empirical relationships for computation:

$$X_{srx} = 1 - \exp\left[-\ln 2\left(\frac{t}{t_{0,5}}\right)^{n_{srx}}\right] \tag{6}$$

$$t_{0,5} = A_1 d_0^{\alpha_1}\bar{\varepsilon}^{-n}\dot{\bar{\varepsilon}}^{m_1}\exp\left\{\frac{\beta_1}{T}\right\} \qquad \text{– sign in n1} \tag{7}$$

$$d_{srx} D_s \cdot X_{srx}{}^{\sigma_{srx}} \tag{8}$$

$$D_s = A_2 d_0{}^{\alpha_2}\bar{\varepsilon}^{n_2}\dot{\varepsilon}_f{}^{m_2}\exp\left(\frac{\beta_2}{T}\right) \tag{9}$$

where: X_{srx} – static recrystallised fraction,
$t_{0,5}$ – time for 50% recrystallisation,
d_{srx} – size of the recrystallised grain,
$\bar{\varepsilon}$ – accumulated strain during the deformation phase,
$\dot{\bar{\varepsilon}}$ – is the average stain rate during the deformation phase,
D_s – recrystallised diameter for static recrystallisation,
d_0 – initial grain size before recrystallisation.

For the austenite grain growth a formula was used:

$$d_{cr}{}^{\alpha_3} - d_0{}^{\alpha_3} = A_3\exp\left(\frac{\beta_3}{T}\right)\cdot t \tag{10}$$

where: t – time since the beginning of growth,
d_{cr} – size of the grain after growth,
d_0 – size of the grain before growth.

3. Investigated material

The numerical analysis of the process of rolling 50x20 mm flat bars was made for steel S355. The coefficients characterizing the material studied were assumed based on the work by Stradomski [3]. Table 1 summarizes the determined values of the coefficients occurring in the equations that describe the development of microstructure during rolling (6÷10). Based on the studies carried out in work [3], it was assumed that the average austenite grain size before the rolling process was 300μm.

TABLE 1
Values of the coefficients used in formulae (6÷10)

Index / Coefficient	1	2	3
A	6,1 $cdot$ 10^{-13}	45	$1{,}1 \cdot 10^7$
α	-0,14	0,374	2
β	32475	-3001	-13591,54
n	-1,929	-0,6	
m	-0,288	-0,1	
a_{srx}	0,663		
n_{srx}	1		

Based on the analysis of the flow curves curves of experimental steel for strain rates at which the processes of rolling 50x20 mm flat bars progress, which is performed in works [3, 5, 6], it can be assumed that the reconstruction of the structure occurs only during static recrystallization.

4. Initial parameters and rolling and cooling schema

Theoretical studies were carried out for three variants: Variant I -– classical rolling (without accelerated cooling), Variant II -– rolling with one section of accelerated cooling, and Variant III -– rolling with two accelerated cooling sections. Figures 1÷3 show the applied schemes of rolling 50x20 mm flat bars.

The shape and dimensions of passes roll diameters, and rolling speeds were taken based on the technical documentation of a Polish Rolling Mill. The initial rolled band temperature, as determined from measurements, was 1120°C. Rolling for Variant I was conducted in 13 passes in the successive stands of a rolling line (Fig. 1).

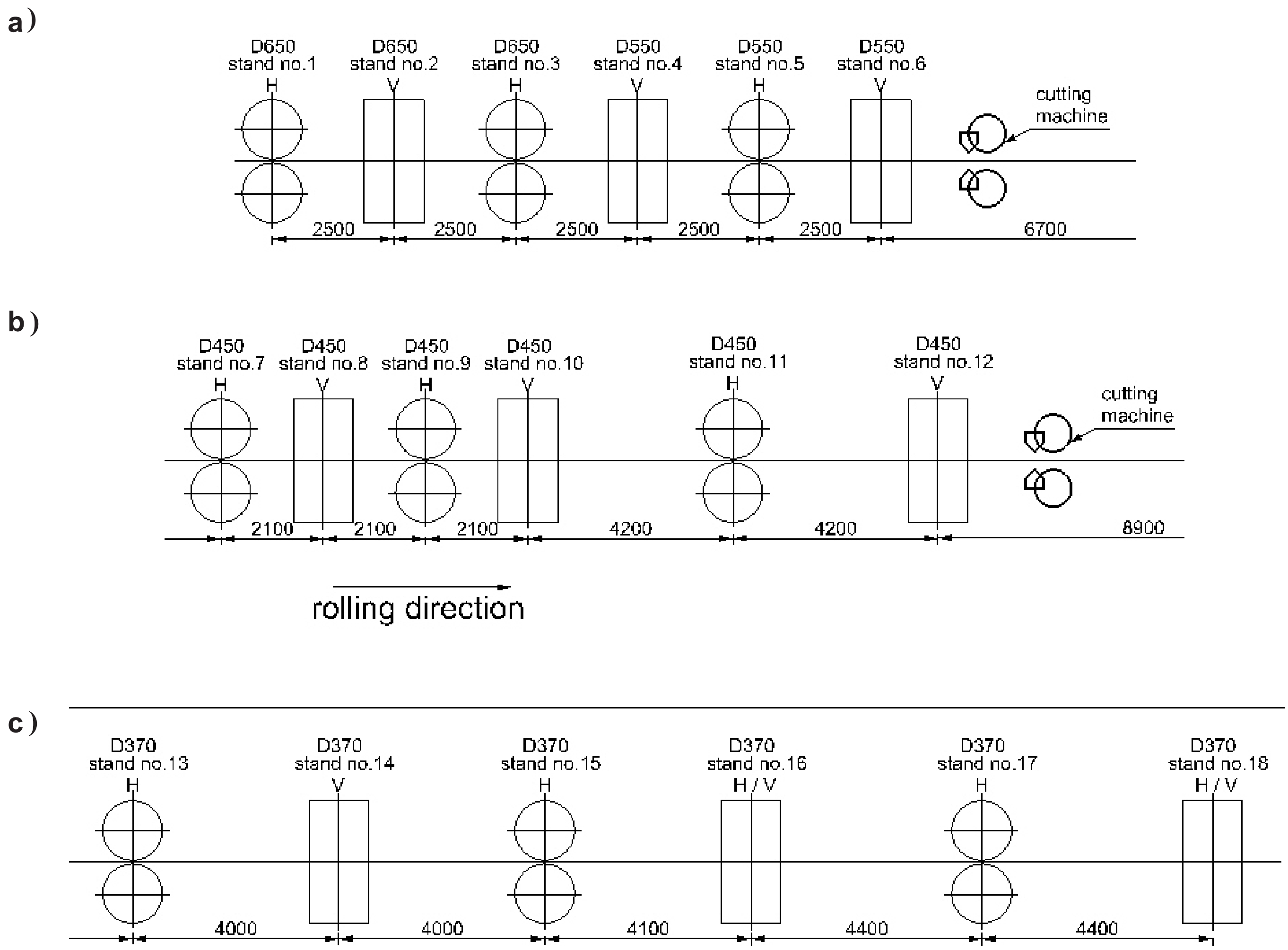

Fig. 1. Scheme of rolling 50x20 mm flat bars without accelerated strip cooling in the rolling line: a) roughing group, b) intermediate group, c) finishing group – Variant I

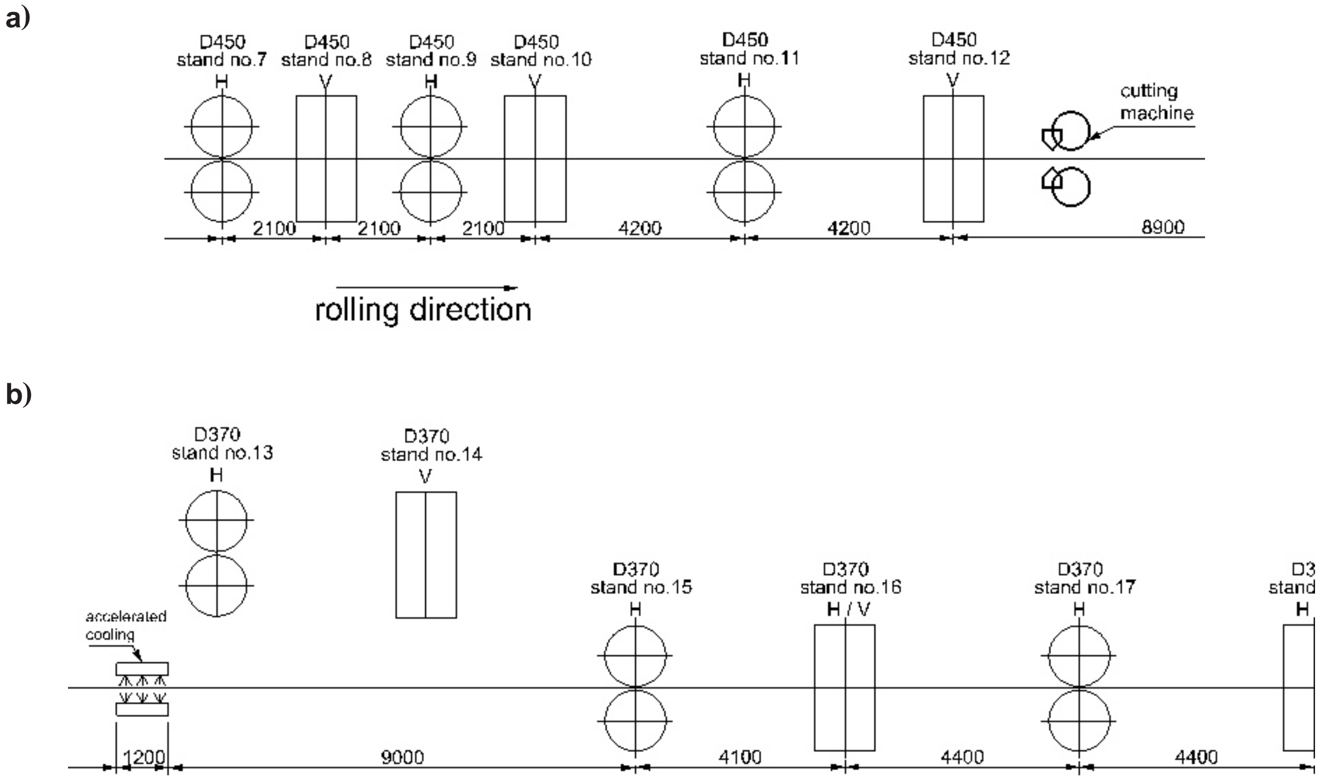

Fig. 2. Scheme of rolling 50x20 mm flat bars with one accelerated cooling section applied: a) intermediate group, b) finishing group – Variant II

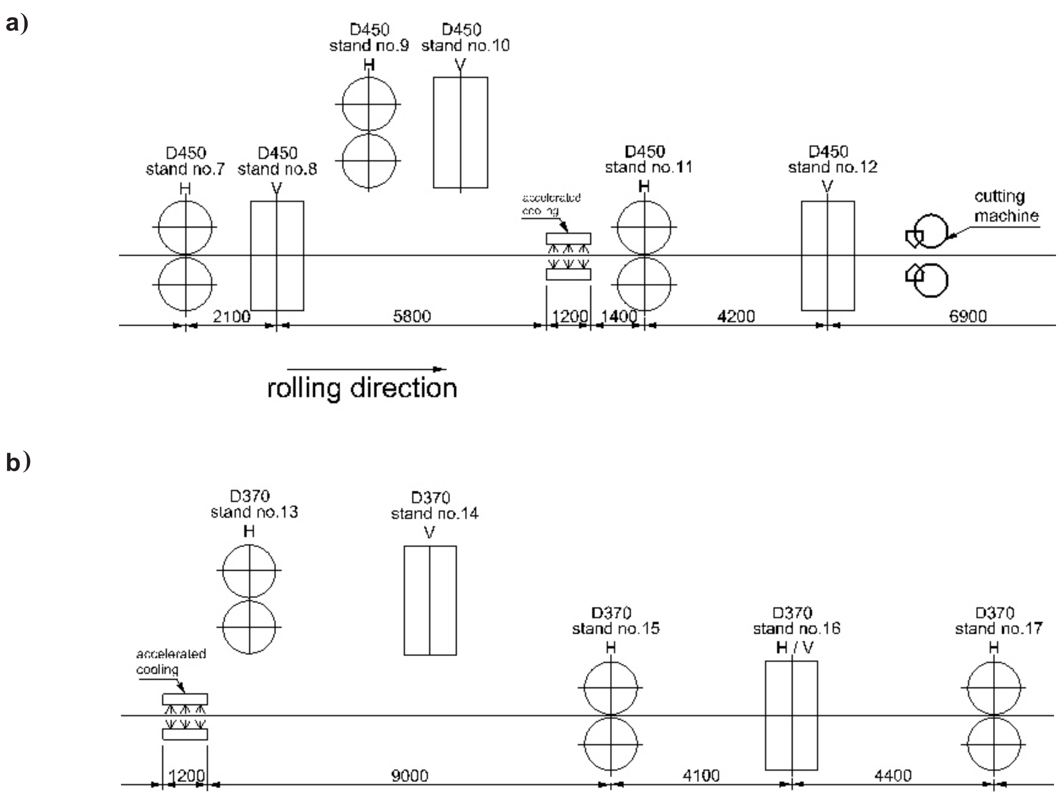

Fig. 3. Scheme of rolling 50x20 mm flat bars with two accelerated cooling section applied: a) intermediate group, b) finishing group – Variant III

During rolling according to Variant II, one cooling section was introduced before the last two passes over a 1.2 m-long segment, after Pass 12 (Fig. 2b). In Variant II, the rolling of band in Stands 13 and 14 was eliminated and transferred to the two last rolling line stands, i.e. Stands 17 & 18 (Fig. 2b).

For rolling Variant III, accelerated cooling was used in two locations of the rolling line. The first, approx. 1.2 m-long, accelerated cooling section was located between Stands 10 and 11, thus eliminating band rolling in Stands 9 and 10 (Fig. 3a). The second accelerated strip cooling was located, similarly as for Variant II, before the two last passes (Fig. 3b). As the result of the necessity of strip rolling in Stands 9 & 10 and 13 & 14, the rolling process would end in Stand 17.

Moreover, the following conditions of the process of rolling 50x20 mm flat bars were adopted: tool temperature: 60°C, ambient temperature: 20°C, the coefficient of heat exchange with the tools: 3000 W/m^2 K, the coefficient of heat exchange with the environment: 100 W/m^2 K, the coefficient of heat exchange with the cooling medium during accelerated cooling: 5500 W/m^2 K, the friction factor: 0.75, the friction coefficient: 0.3.

5. Determination of the grain size of austenite recrystallized statically during rolling 50x20 mm flat bars

On the basis of the theoretical analysis of the process of rolling 50x20 mm flat bars, the grain size of austenite was determined. Figures 4¸5 show diagrams of austenite grain size evolution during rolling 50x20 mm flat bars for the rolling variants under analysis. For all cases the minimum grains size of austenite size were observed surface zone and maximum grains size of austenite were observed in central zone of the flat bar. Looking at the data in Fig. 4, it can be noticed that the austenite grain undergoes size reduction as strip is rolled in successive rolling stands

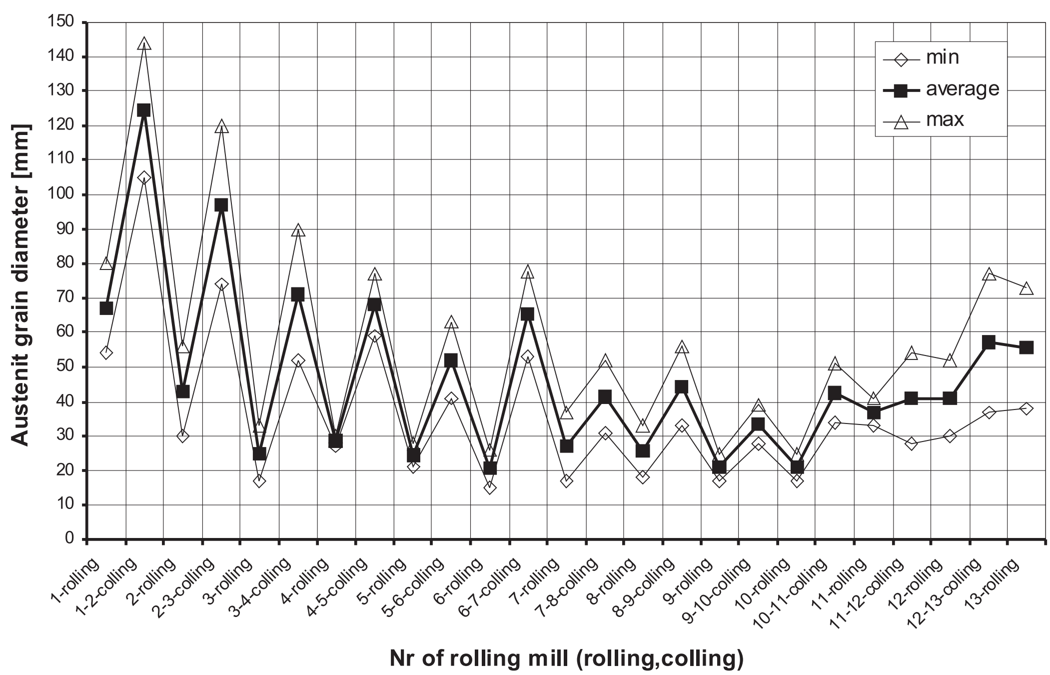

Fig. 4. Austenite grain size variation during rolling 50x20 mm flat bars (Variant I – without accelerated cooling in the rolling line)

However, due to low rolling speeds and distances between stands, cooling of the band takes place, which causes austenite grain growth. In addition, due to the rolling reduction distribution applied in rolling of 50x20 mm flat bars in the last passes (Stands 12 & 13), the deformations are relatively small, which inhibits austenite grain size reduction. Between Stand 12 and Stand 13, a rapid grain growth takes place as the band moves, because off deformation in Stand 13 the grain cannot be refined.

When analyzing the data related to Variant II of rolling, as shown in Fig. 5, it can be noticed that the application of accelerated cooling between passes 12 and 13 (Stands 12 – 15) does not influence significantly the austenite grain size in the strip rolled. This is caused by a small deformation in the last pass (Stand 15), preventing the austenite grain from refining.

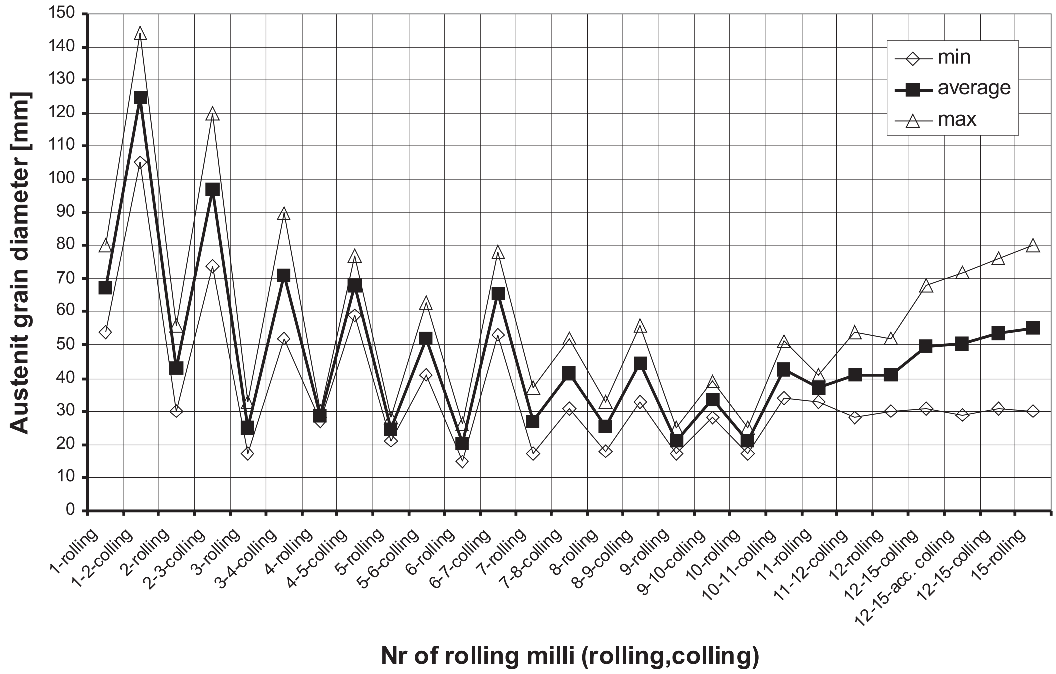

Fig. 5. Austenite grain size variation during rolling 50x20 mm flat bars (Variant II – with one accelerated strip cooling in the rolling line)

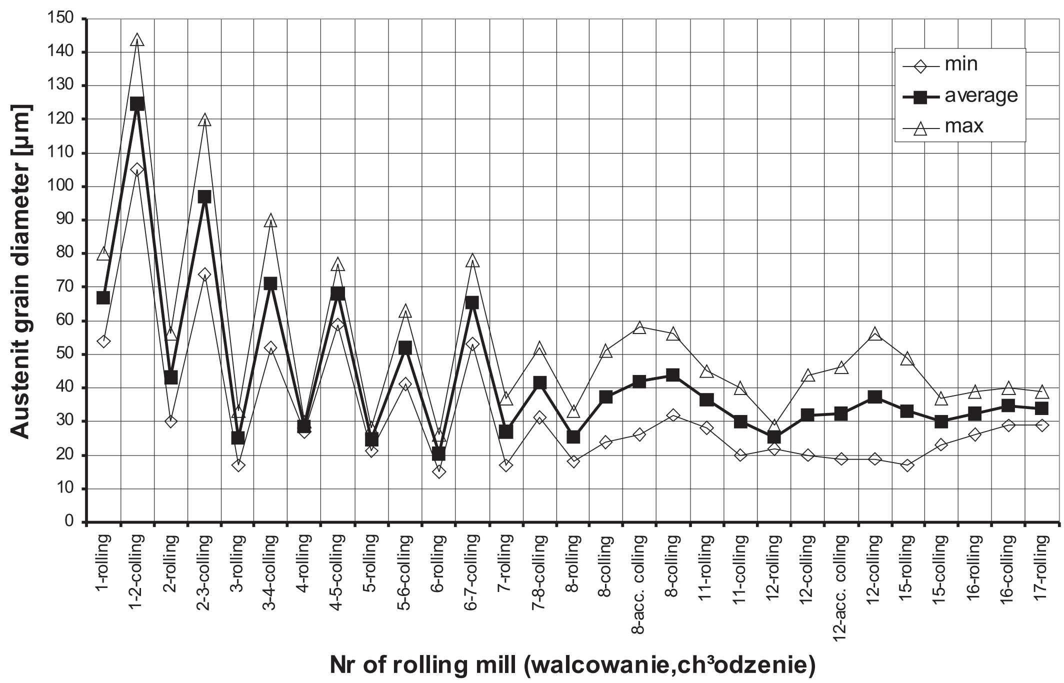

Fig. 6. Austenite grain size variation during rolling 50x20 mm flat bars (Variant II – with two accelerated strip cooling in the rolling line)

A significant change in austenite grain size after the last pass (Stand 17), on the other hand, was observed when rolling Variant III was used (Fig. 7.2.3). The application of an accelerated cooling zone between passes 8 – 9 (Stands 8 – 11) made it possible to stop the grain growth in the cooling zones between passes 9 – 10. While the application of an accelerated cooling zone before Pass 11 allowed a reduction of band temperature that enabled an average austenite grain smaller by 36% than the one obtained both in the traditional technology (Variant I) and with one accelerated cooling (Variant II) to be achieved in the last three passes.

When analysing the theoretical study results its was also observed that a more uniform grain size distribution on the rolled bar cross-section was obtained in Variant III compared to Variants I and II.

Within the theoretical studies carried out, the basic energy and force parameters of the 50x20mm flat bar rolling process were also determined. The determined values of the total roll separating force and rolling power for Variants I and III are shown in Figs. 7÷8. When analysing the data in Fig. 7 it can be noticed that the application of accelerated rolling in Variant III resulted in an increase in roll separating force by, respectively, 23% in Pass 9, 34% in Pass 10, 42% in pass 11, 43% in Pass 12, and 17% in pass 13. With the increase in the magnitude of roll separating force, an increase in both rolling moment and rolling power occurred.

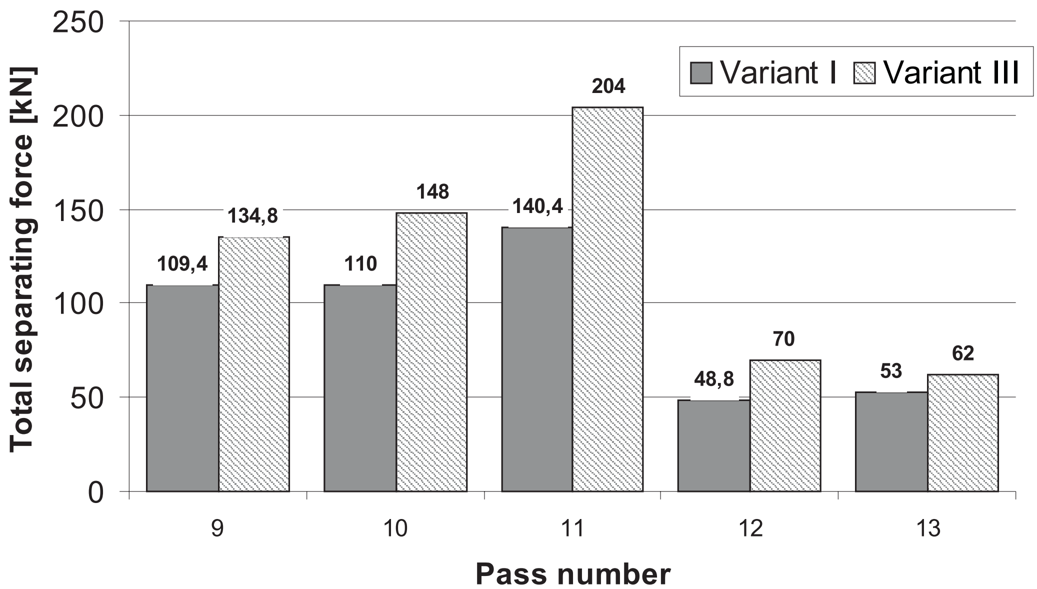

Fig. 7. Total separating force during rolling 50x20 mm flat bars for Variant I and Variant III

The analysis of the data in Fig. 11.3 shows that the rolling power increased in pass 9 from 29.16 to 39.88 [kW] (a 35% increase), and in pass 10 from 29.24 to 34.6 [kW] (an approx. 18% increase); for Pass 11 the rolling power increased from 20.4 to 29.9 [kW] (i.e. by approx 46%), in Pass 12 from 7.4 to 10.6 [kW] (i.e. by approx. 43%); while for the last pass (Pass 13), a rolling power increase from 5.3 to 7.1 [kW] (i.e. by approx. 34%) occurred.

By comparing the values of energy and force parameters obtained for Variant III with the permissible rolling power values for the Rolling Mill under analysis it can be found, however, that they do not exceed the permissible loads of the main drives.

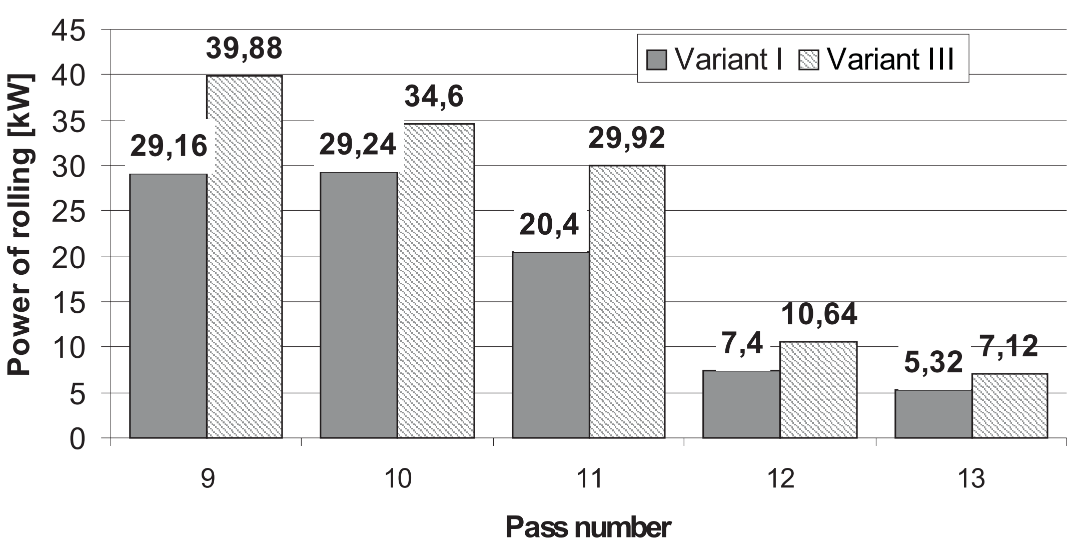

Fig. 8. Power of rolling during rolling 50x20 mm flat bars for Variant I and Variant III

6. Conclusions

The application of normalizing rolling will result in substantial microstructure changes in grain size and homogeneity, and, by eliminating the additional normalizing treatment, will enhance the competitiveness of bars produced in the continuous Rolling Mill.

From the numerical modeling results, a variable-size austenite grain was found to occur, depending on the rolling technology used. During the traditional rolling process, as well as during normalizing rolling, structure refinement takes place. However, in the case of traditional rolling this effect occurs only in a narrow area of contact between the strip and the tool.

From the performed numerical analysis it can be found that the application of accelerated cooling in the rolling line for the single cooling variant caused an increase in the average austenite grain size, while the application of two cooling sections in the rolling line resulted in austenite grain refinement.

The increase in energy parameters for the accelerated cooling variant is due to the reduction of rolled strip temperature resulting from the application of accelerated cooling in the rolling line.

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