Development of asymmetric cold rolling technology of high-strength steel grades in order to exclude intermediate annealing operations

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Abstract. The technological process of manufacturing cold-rolled strip with a thickness of 0.5-1.5 mm from high-strength steel grades on cold rolling mills can consist of 2 or even 3 operating cycles "cold rolling - intermediate annealing". This is due to a significant hardening of such steels during cold rolling and, as a result, limitations on the maximum allowable rolling forces. Each additional operating cycle "cold rolling - intermediate annealing" significantly increases production costs and reduces the productivity of the technological process. One of the promising ways to reduce the rolling force is the asymmetric rolling. Rolling at different circumferential speeds of work rolls driven by two independent motors is the most suitable way to implement asymmetric rolling technology in industry. The paper presents data on the operation of the main electric drives of a five-stand industrial mill during symmetric and asymmetric cold rolling. Speed ratio of the work rolls was varied in the range from 1.0 to 1.5. Electrical and power parameters were calculated, measured and compared. Based on numerical simulation, laboratory and industry experiments it was shown that the asymmetric cold rolling makes it possible to reduce the rolling forces, increase the thickness reduction per pass and, as a result, obtain a thinner strip without the use of intermediate annealing.

Introduction

In the production of cold-rolled strip from high-strength steel grades with a final thickness of 0.5-1.5 mm on cold rolling mills, the technological process consists of 2 or even 3 operating cycles "cold rolling – intermediate annealing". This is due to the significant work hardening of such steels during cold rolling, and, as a result, the limitations of rolling forces. To be able to obtain a thin cold-rolled strip, intermediate annealing is required. Intermediate annealing is a recrystallization annealing at a temperature of 600 to 710 °C of work-hardened rolled metal in furnaces with a protective atmosphere. The duration of 1 intermediate annealing is 38-44 hours. Thus, each operating cycle "cold rolling – intermediate annealing" significantly increases production costs, reduces the productivity of the technological process.

One of the promising non-traditional ways to improve the mechanical properties, the accuracy of the geometric dimensions of the strips, as well as to reduce the rolling force is the speed asymmetry of the work rolls [1-3]. With a decrease in the thickness of sheets and strips, the effect of reducing the rolling force increases. Rolling with different circumferential speeds of the work rolls, when both rolls are driven by two independent motors, is the most suitable way to implement the asymmetric rolling technology in industry. Asymmetric rolling due to purposefully created differences in the circumferential speeds of the work rolls is also called “differential speed rolling”. For such a process, a degree of asymmetry is defined by a ratio of circumferential speeds υ_1 and υ_2 of the work rolls:

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$$S_R = \frac{v_1}{v_2}. \quad (1)$$

where S_R is the speed ratio and $v_1 > v_2$.

Previous extensive theoretical and experimental studies [1-11] of asymmetric rolling processes have revealed the positive aspects of speed asymmetry, which consist primarily in the possibility of a significant reduction in rolling force, reduction of elastic deformations of the stand, and an increase in thickness reductions per pass and the possibility of obtaining thinner strips compared to the conventional rolling process.

The mechanics of the asymmetric rolling process is based on the creation of additional shear deformations in the rolled metal. In contrast to the symmetric process, a shear deformation zone appears in the deformation zone during asymmetric rolling; a zone in which the forces of contact friction from the side of the fast (rotating at a higher speed) and slow (rotating at a lower speed) rolls are directed in opposite directions [11].

The practical application of asymmetric rolling is usually preceded by a series of preliminary calculations and experiments to determine the ultimate loads of mechanical and electrical equipment. The load on the transmission and drive of the fast roll noticeably increases, and the drive of the slow roll can switch to the generator (brake) mode. To eliminate the maximum unacceptable loads of electric drives, determining the extreme values of the asymmetry coefficient is an important task. The range of allowable values of speed asymmetry is determined by two restrictions: 1) the maximum allowable torque of the fast roll engine; 2) the minimum torque of the slow roll motor. The first condition excludes overloading and shutdown of the electric drive and the second one ensures that the slow roll engine is not allowed to switch to the generator (brake) mode. When choosing the asymmetry coefficient, it is necessary to take into account the factors affecting the quality of the strip surface and the stability of the rolling process. For example, the friction coefficient in the deformation zone and the temperature of the rolls with all the ensuing consequences depend on the amount and composition of the cutting fluid. The stability of the process is determined by the setting of local systems for controlling the speed of electric drives, the tension and thickness of the strip in the interstand gaps, and the degree of field weakening in systems with two-zone speed control.

The paper presents data on the operation of the main electric drives of a 5-stand industrial mill during symmetric and asymmetric cold rolling. Speed ratio of the work rolls was varied in the range from 1.0 to 1.5. Electrical, power and force parameters were calculated, measured and compared.

Research Method

Continuous 5-stand mill "630" (Fig. 1) is designed for cold rolling of narrow strip with a final thickness of 0.5-4.5 mm and a width of 250-500 mm from various steel grades. The individual electric drives of the work rolls are made according to the "thyristor converter – motor" system. Each of the work rolls is driven by a DC motor. Diameters of the work rolls and back-up rolls are 420 mm and 900 mm, respectively. The mill is equipped with an automatic tension and thickness control system. The main parameters of the electric drives (armature and excitation currents, voltage, and motor speed) were recorded using the "MONITOR" information electronic system. In addition, non-electrical parameters were recorded: the thickness and width of the strip, tension and rolling force. The experiment was carried out during cold rolling of high-strength steel (Table 1) at a rolling speed of 6 m/s.

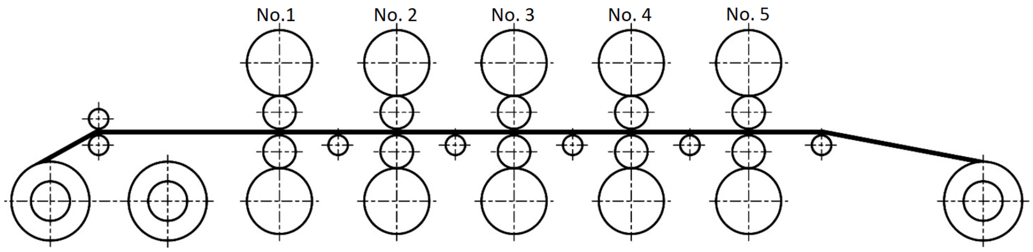

Fig. 1. Scheme of the continuous 5-stand mill "630"

The conventional technological process for the production of cold-rolled strip from high-strength steel includes the following operations: cold rolling (in 5 passes) from a thickness of 2.8 mm to 2.0 mm → intermediate annealing → cold rolling (in 5 passes) from a thickness of 2.0 mm to 1.3 mm. The task of the industrial experiment was to assess the technological feasibility of producing cold-rolled strip from high-strength steel according to the scheme: cold rolling (in 5 passes) from a thickness of 2.8 mm to 1.3 mm without intermediate annealing (Table 2).

Table 1. Chemical composition of high-strength steel.

Chemical composition, %														
C	Si	Mn	S	P	Cr	Ni	Cu	Al	Mo	V	Ti	Nb	N	B
0.67	0.27	0.97	0.0051	0.012	0.032	0.057	0.070	0.036	0.0060	0.0065	0.0050	0.0022	0.0054	0.0005

Table 2. Rolling pass schedule.

Stand No.	1	2	3	4	5
Entry thickness, mm	2.8	2.32	1.91	1.59	1.38
Exit thickness, mm	2.32	1.91	1.59	1.38	1.28
Thickness reduction, %	17.14	17.67	16.75	13.21	7.25

The industrial experiment included rolling in four modes: 1) symmetric rolling (mode 1); 2) asymmetric rolling with $S_R = 1.1$ (mode 2); 3) asymmetric rolling with $S_R = 1.2$ (mode 3) 4) asymmetric rolling with $S_R = 1.5$ (mode 4). In all cases, rolling in stands No. 1 and No. 5 was symmetrical. Asymmetry was created only in stands No. 2, No. 3 and No. 4. At the same time, the speed asymmetry was set to be the same in stands No. 2, No. 3, No. 4. With asymmetric rolling, the upper work roll had a higher speed than the lower one in all cases. For all variants of the experiment, the same rolling pass schedule was taken (Table 2).

The initial experimental data were oscillograms of electrical and power parameters exported from the "MONITOR" program in the form of data arrays. They are tabulated functions of time at a discrete point of 0.001 s. Their further processing was carried out in the MATLAB Simulink environment, which is well suited for working with large amounts of information. Due to the unequal operating time of the mill during symmetric and asymmetric rolling, the calculations were carried out for the steady state operation of electric drives. Determination of the required electrical and power parameters – power consumption, power consumption, torque and rolling power is made according to the well-known formulas given below.

The electrical power consumed by DC motor and the power consumption were calculated:

$$P_{el} = UI_a. \tag{2}$$

where U is motor voltage, V; I_a is armature current, A.

$$\Delta W_{el} = \int_{t_0}^{t} P_{el}(t)dt. \tag{3}$$

The calculation of the rolling torque and rolling power was carried out in accordance with the simplified scheme of the mechanical part of the electric drive (Fig. 2). This takes into account the efficiency of motors and gearboxes.

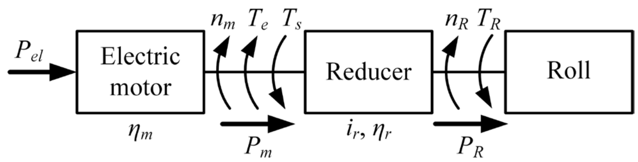

Fig. 2. Simplified scheme of the mechanical part of the electric drive.

The rolling torque was calculated as follows:

$$T_R = \frac{UI_a\eta_m\eta_r i_r}{\omega_m}. \quad (4)$$

where $\eta_m = 0.924$, $\eta_r = 0.95$ are motor efficiency and reducer efficiency; ω_m is angular speed of the motor, rad/s; i_r is gear ratio (i_r = 1.764; 1.474; 1.238; 1.088; 1,000 for stands No. 1-No. 5, respectively).

The rolling power was calculated as follows:

$$P_R = \frac{T_R\omega_m}{i_R}. \quad (5)$$

Equations (4) and (5) did not take into account friction torque and interstand tension. Average (X_{avg}) and root-mean-square (X_{rms}) values of the functions of electrical, power and force parameters (armature current, power, torque, etc.) were calculated according to instantaneous values of the $x(t)$ functions:

$$X_{avg} = \frac{1}{t-t_0}\int_{t_0}^{t} x(t)dt. \quad (6)$$

$$X_{rms} = \sqrt{\frac{1}{t-t_0}\int_{t_0}^{t} x^2(t)dt}. \quad (7)$$

The average and root-mean-square values were calculated in the steady state operation of the drive for the time interval $t - t_0$, which was 60 s. During the same time, the consumption of electricity was also determined. The block diagram of the model for processing experimental data, shown in Fig. 3 was implemented in MATLAB Simulink [12].

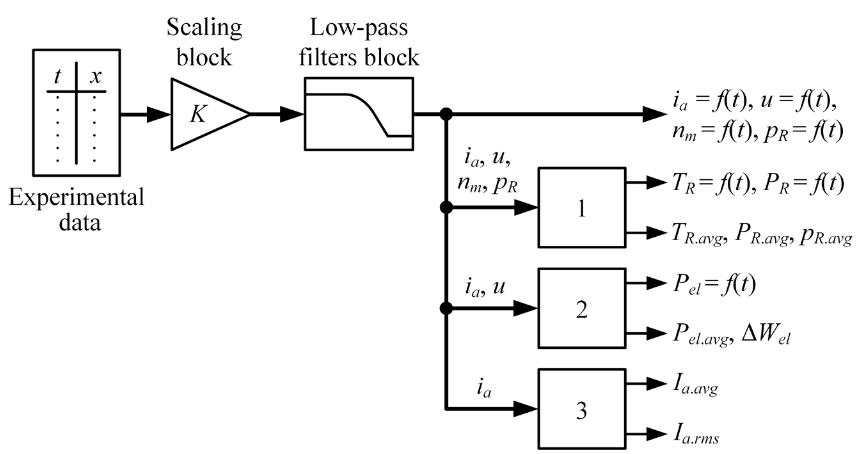

Fig. 3. Flow chart of the model for experimental data processing (where 1 is a power and force calculation block; 2 is an electric power and electricity consumption calculation block; 3 an average and root-mean-square armature current calculation block)

Simulation Results and Discussion

Symmetric rolling (mode 1) and asymmetric rolling with $S_R = 1.1$ and $S_R = 1.2$ (modes 2 and 3, respectively) were completed without any problems. The thickness of the strip along the entire

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length and width was within the tolerance range. The rolling of the 4th mode with $S_R = 1.5$ could not be completed due to overheating of the rolls due to high frictional heating under conditions of insufficient cooling capacity of the emulsion.

The speed asymmetry caused a noticeable decrease in rolling forces in all stands, and this was accompanied by a decrease in the total rolling torque and power, with the exception of the first stand, where there was a slight increase in power. This was caused by a decrease in tension in the section "decoiler – stand No. 1" during asymmetric rolling. During asymmetric rolling, the armature current increased on the upper (faster) roll, and decreased on the lower (slower) roll. At the same time, the total load of the upper and lower rolls during asymmetric rolling was significantly reduced (at least 15%) compared to symmetrical rolling.

Oscillograms of the armature currents and rolling force of stand 2 during symmetric and asymmetric rolling in a steady-state operation of motors are given in Figs. 4-6. Comparing of the torques, power and force parameters for symmetric and asymmetric rolling are shown in Figs. 7-9.

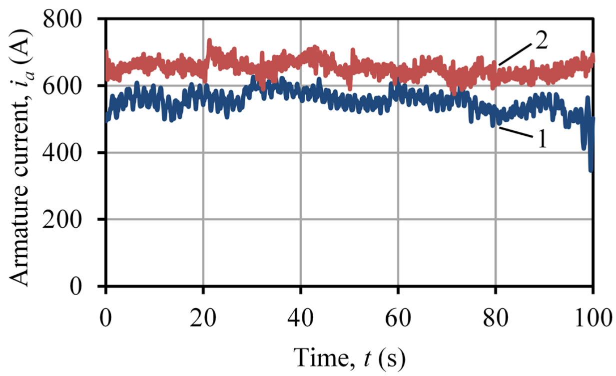

Fig. 4. Oscillograms of armature currents of motor of top roll of stand 2 (1 is symmetric rolling; 2 is asymmetric rolling).

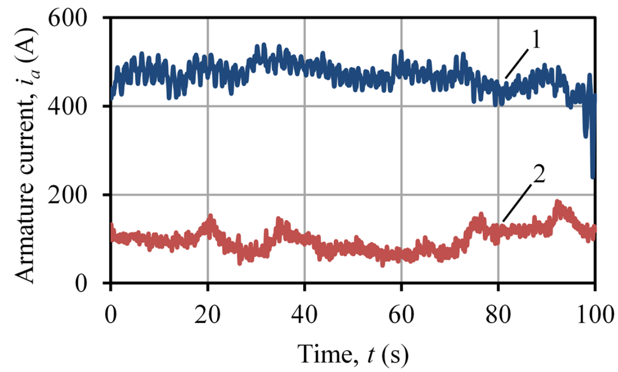

Fig. 5. Oscillograms of armature currents of motors of bottom roll of stand 2 (1 is symmetric rolling; 2 is asymmetric rolling).

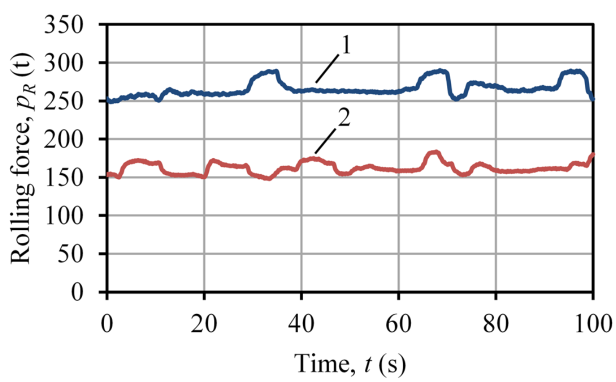

Fig. 6. Oscillograms of armature currents of rolling force in stand 2 (1 is symmetric rolling; 2 is asymmetric rolling).

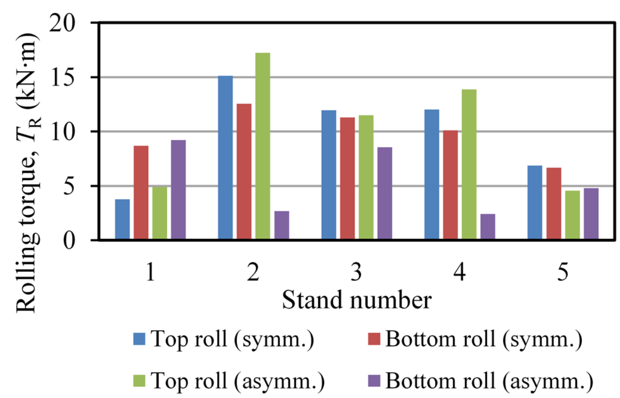

Fig. 7. Torques compared for symmetric and asymmetric rolling.

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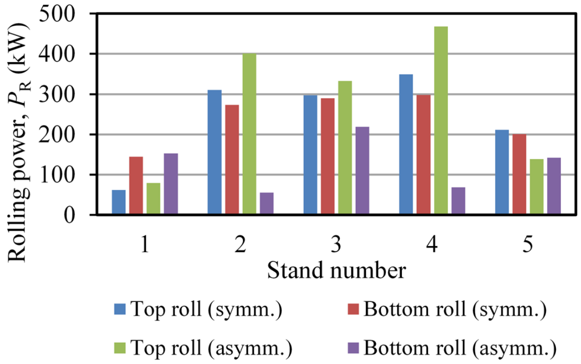

Fig. 8. Powers compared for symmetric and asymmetric rolling.

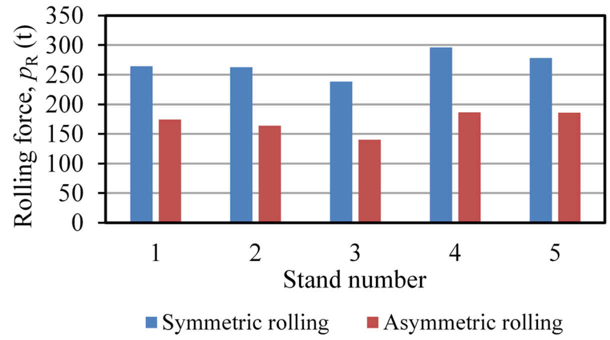

Fig. 9. Forces compared for symmetric and asymmetric rolling.

Table 3 shows a comparison of the experimental results presented for two cases – symmetric rolling (mode 1) and asymmetric rolling with $S_R = 1.2$ (mode 3). A comparison of the electricity consumption of the main drives showed that asymmetric rolling is a more efficient process compared to symmetric rolling. The difference was just over 15%.

Table 3. Comparison of electricity consumption.

Stand No.	1	2	3	4	5	$\sum \Delta W_{el}$
Rolling mode	Electricity consumption ΔW_{el}, kW·h					
Symmetric rolling	3.931	11.070	11.130	12.190	7.811	46.13
Asymmetric rolling ($S_R = 1.2$)	4.409	8.668	10.470	10.200	5.337	39.08
Difference, %	+10.8	-21.7	-5.93	-16.3	-31.7	-15.3

For asymmetric rolling, the following condition must be satisfied:

$$S_R = \frac{v_1}{v_2} < \frac{h_0}{h_1}. \tag{8}$$

where v_1 is the speed of the fast work roll; v_2 is the speed of the slow work roll; h_0 is the thickness before the rolling pass; h_1 is the thickness after the rolling pass.

That is, the speed ratio during asymmetric rolling should not be greater than the ratio of the input and output thicknesses of the strip in the corresponding pass.

The experiment on the implementation of the technology of asymmetric rolling in industrial conditions was carried out at a reduced speed (6 m/s), which differs significantly from the maximum. In normal speed mode, the motors operate with field weakening. The manual setting of the speed asymmetry, tested in this experiment, is planned to be implemented in the automatic mode for each stand individually, taking into account the rolling pass schedule and a steel grade.

The economic effect of using asymmetric rolling technology is to reduce the cost of additional cold rolling and intermediate annealing operations. In particular, when additional cold rolling operations are excluded, the costs for energy resources (electricity, technical water, compressed air), costs for auxiliary materials (liquid lubricant, inter-operational coil packaging), costs for rolls (transshipment, regrinding) are reduced. With the exclusion of additional intermediate annealing operations, the costs on process fuel (natural gas) and the costs on energy resources (electricity, pure nitrogen, hydrogen, industrial water) are reduced. In addition, the overall productivity of the technological process is significantly increased, primarily due to the elimination of intermediate annealing operations, the duration of which is 38...44 hours.

Conclusion

According to the results of an industrial experiment, the technical feasibility of implementing the technology of asymmetric rolling in a continuous 5-stand mill was confirmed. This technology can be used to reduce the number of operating cycles "cold rolling - intermediate annealing" in the production of a strip with a thickness of 0.5-1.5 mm from high-strength steel grades to reduce the cost of production and increase the productivity of the technological process.

A reduction in the total consumption of electricity by the main drives of 5 stands by 15% was established. Additional statistical analysis is required to identify patterns and confirm. After asymmetric rolling, there were no discontinuities, microcracks or microfractures in the strip material, and the mechanical properties met the requirements of consumers. With asymmetric rolling, the thickness of the strip along the entire length and width was within the tolerance field.

The results of investigation can be used for design of effective asymmetric cold rolling technology which makes it possible to reduce the rolling forces, increase the thickness reduction per pass and, as a result, obtain a thinner strip without the use of intermediate annealing.

Acknowledgements

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References

[1] G. Vincze, F.J.P. Simões, M.C. Butuc Asymmetrical rolling of aluminum alloys and steels: a review, Metals (2020) 10(9):1126 https://doi.org/10.3390/met10091126

[2] D. Pustovoytov, A. Pesin, P. Tandon Asymmetric (hot, warm, cold, cryo) rolling of light alloys: a review, Metals (2021) 11(6):956 https://doi.org/10.3390/met11060956

[3] H. Yu, C. Lu, A.K. Tieu, H.J. Li, A. Godbole, S.H. Zhang, Special rolling techniques for improvement of mechanical properties of ultrafine-grained metal sheets: a review, Adv. Eng. Mat. 18 (2016) 754-769 https://doi.org/10.1002/adem.201500369

[4] S.S. Dhinwal, C. Ernould, B. Beausir, Facilitating the occurrence of dynamic recrystallization in plain extra low-carbon steel by warm asymmetric rolling, Materials Characterization 189 (2022) 111942 https://doi.org/10.1016/j.matchar.2022.111942

[5] J. Wang, X. Liu, X. Sun, Study on the relationship between asymmetrical rolling deformation zone configuration and rolling parameters, Int. J. Mech. Sci. 187 (2020) 105905 https://doi.org/10.1016/j.ijmecsci.2020.105905

[6] D. Konstantinov, D. Pustovoitov, A. Pesin Influence of microstructure on inhomogeneity of stress and strain in the deformation zone during asymmetric cold rolling of ferritic-pearlitic steels, Procedia Manufacturing 50 (2020) 514-519 https://doi.org/10.1016/j.promfg.2020.08.093

[7] A. Kawalek, The theoretical and experimental analysis of the effect of asymmetrical rolling on the value of unit pressure, J. Mater. Process. Technol. 157-158 (2004) 531-535 https://doi.org/10.1016/j.jmatprotec.2004.07.142

[8] H. Dyja, J. Markowski, D. Stoiniski, Asymmetry of the roll gap as a factor improving work of the hydraulic gauge control in the plate rolling mill, J. Mater. Process. Technol. 60 (1996) 73-80 https://doi.org/10.1016/0924-0136(96)02310-2

[9] M. Philipp, W. Schwenzfeier, F.D. Fischer, R. Wodlinger, C. Fischer, Front end bending in plate rolling influenced by circumferential speed mismatch and geometry, J. Mater. Process. Technol. 184 (2007) 224-232 https://doi.org/10.1016/j.jmatprotec.2006.11.027

[10] D. Kasai, A. Komori, A. Ishii, K. Yamada, S. Ogawa, Strip Warpage Behavior and Mechanism in Single Roll Driven Rolling, ISIJ Int. 56 (2016) 1815-1824 https://doi.org/10.2355/isijinternational.ISIJINT-2016-188

[11] Y. Tian, Y.C. Guo, Z.-D. Wang, G.-D. Wang, Analysis of rolling pressure in asymmetrical rolling process by slab method, J. Iron Steel Res. Int. 16 (2009) 22-26 https://doi.org/10.1016/S1006-706X(09)60055-8

[12] A.A. Bochkarev, G.P. Kornilov, Understanding the electric drive parameters of energy and forces during asymmetric rolling, Magnitogorsk rolling practice 2022. Magnitogorsk, NMSTU Publ. (2022) 48-49