STUDY OF THICKNESS CONTROL OF STRIP HEAD SECTION USING MATHEMATICAL SIMULATION METHODS

V.R. Khramshin, *Magnitogorsk State Technical University (Magnitogorsk, Russian Federation)*
A.S. Karandaev, *South Ural State University (Chelyabinsk, Russian Federation)*
A.A. Radionov, *South Ural State University (Chelyabinsk, Russian Federation)*
R.R. Khramshin, *Magnitogorsk State Technical University (Magnitogorsk, Russian Federation)*

The authors participated in the modernization of the automatic strip thickness control system of OJSC "Magnitogorsk Iron and Steel Works" 2000 hot rolling mill (OJSC "MMK"). The article offers a brief description of the implemented automatic strip thickness control system developed on the basis of hydraulic screwdown mechanisms. Industrial trials found significant thickness deviation of up to 10% in the strip head section. As a result the length of strip head section with thickness deviation can achieve 40–50 m after the last finishing rolling stand of the mill. The authors offer a new way of strip head thickness control by means of roll gap increase before the strip grip and its further decrease to the required gauge by hydraulic screwdown adjustment during rolling. They also studied the algorithm of roll gap control and factors influencing its adjustment. The research group developed mathematical model of the electromechanical system "stand electric drive – hydraulic screwdown mechanism" taking into account the interrelation of their drives through the rolled metal. The mathematical model of the stand electric drive is developed in the system of two-region speed control. The hydraulic screwdown mechanism can be described by linearized differential equations of fluid flow rate, servo valve for small coordinate increment and forces relationship in the rolling stand. The model consists of a system of differential equations describing the rolled strip as a control object and mathematical description of automatic screwdown mechanism control. The validity of the developed mathematical model was also proved. The authors studied dynamic modes for various parameters of roll gap control and determined the optimum control parameters providing the minimum thickness deviation of the strip head section. The results of the first strips rolling proved that the developed method is quite effective and can be recommended for advanced automatic strip thickness control.

Keywords: mathematical model, hot rolling mill, control system, strip, control system, thickness deviation.

The revamping of the automatic process control system of the finishing train of OJSC "MMK" 2000 hot rolling mill included modernization of the automatic strip thickness control system [1–3]. The new system is based on the multiprocessor digital controller. Controller enhancement made it possible to develop the advanced digital algorithms of strip thickness control. In order to study the accuracy of strip thickness control and to estimate dynamic parameters of electric drives at the stages of feasibility study and project implementation, it was necessary to develop the dynamic mathematical model of the electromechanical system "stand electric drive – hydraulic screwdown mechanism" taking into account their interrelation through the rolled metal [4-7].

The complex of the automatic strip thickness control system of the finishing train of 2000 hot rolling mill consists of hydraulic screwdown mechanisms, Davy McKee automatic strip thickness control system, work roll bending (system) of rolling stands №10–13 [8–9]. Hydraulic screwdown mechanisms are the main final control actuating link for final thickness control. Electromechanic adjusting screws are applied only for roll gap adjustment during the mill reconstruction. The main adjuster of the automatic strip thickness control system was designed on the principle of indirect thickness measuring in the rolling stand. Exit thickness gauge adjustment is used as the main control method [10–11].

Pilot research carried out on the rolling mill [4, 12] showed significant thickness deviations of the strip head section up to 5–10 % while the standard tolerances are ±3,5 %. The rolling time of the uneven section of the strip is 10–20 s, corresponding to 40–80 m of the strip length on the mill exit. This kind of thickness deviation is characteristic for all the product range of the 2000 rolling mill irrespective of the strip thickness. The analysis of the operating schedule showed that the thickness deviation of the strip head section results from its higher temperature and this deviation along the strip length is mainly characteristic for thin strip rolling.

The research group offers a new way of strip head thickness control by means of roll gap increase before the strip grip and its further decrease to the required gauge by hydraulic screwdown adjustment during rolling [13–18]. Thickness adjustment is carried out according to the diagram given in fig. 1.

The following parameters are depicted in fig. 1: S_c – additional correction value; Δt_1 – time of constant correction value; Δt_2 – time of correction decrease to zero. Colour background shows logic signal of metal presence in the stand.

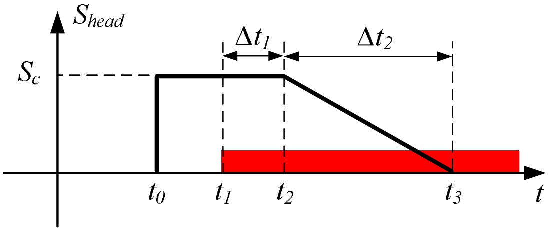

Fig. 1. Diagram of thickness adjustment of strip head section

In order to adjust the parameters of roll gap change of the rolling mill, the authors carried out a number of experiments where they studied rolling of strips with different correction parameters in each stand [9, 13, 15]. The parameters were selected empirically and input to the controller of the automatic process control system. Oscillograph records of strip thickness obtained at different rolling parameters are given in fig. 2.

The first strip (fig. 2, a) was rolled without any additional thickness adjustment of the strip head section. Higher temperature of the strip head section results in – 2,9 % strip thickness deviation. During rolling the temperature of the strip head decreases and consequently the strip thickness increases on the stand exit even though the roll gap does not change. Thickness deviation along the length of the strip head section is 5,6%. In the process of the following strips rolling (fig. 2, b – e) the authors applied method of automatic strip thickness control for the strip head section. Additional correction values (S_c), time of constant correction value (Δt_1) and time of correction decrease to zero (Δt_2) were adjusted in accordance with the values given in fig. 2.

The analysis of findings allowed the authors to make a conclusion that the thickness deviation of the strip head section depends directly on the temperature of the processed strip, initial settings of the roll gap and the value of additional correction S_c.

Changing the value of S_c one can obtain favourable settings for a well defined range of processed strips thus the problem of initial thickness deviation of the strip head section is substantially solved (fig. 2, c). To eliminate the above mentioned thickness deviation along the length of the strip head section due to the temperature difference it is necessary to select the optimal time of constant correction value (Δt_1) and time of correction decrease to zero (Δt_2).

The experiments prove that it is necessary to study rolling processes with different parameters of the strip head section adjustment. Such trials at an operating plant are fraught with emergency stops of the rolling mill. So the authors believe it is necessary to develop the dynamic mathematical model of the system "stand electric drive – hydraulic screwdown mechanism" taking into account their interrelation through the rolled metal. The model structure should include mathematical description of the automatic strip thickness control system algorithms and the system of two-region speed control of the main electric drive [19–21].

The mathematical model of a stand electric drive can be described by the system of equations including equations of the anchor chain and equations taking into account changes of the motor magnetic flux:

$$\begin{cases} E_{d\ i} = \dfrac{\kappa_{t.c.\ i}}{T_{\mu\ i} p + 1} u_{c.\ i}; \\ E_{d\ i} = E + R_{eq.\ i} I_i (T_{eq.\ i} p + 1); \\ M_i = k\Phi_i I_i; \\ E_i = k\Phi_i \omega_i; \\ M_i - M_{s.\ i} = J_{\Sigma\ i} p \omega_i; \\ U_{ex.\ i} = \dfrac{k_{t.ex.\ i}}{T_{\mu\ ex.\ i} p + 1} u_{c.ex.\ i}; \\ I_{ex.\ i} = \dfrac{1 + T_{k\ i} p}{R_{ex.\ i}[1 + (T_{ex.\ i} + T_{k\ i}) p]} U_{ex.\ i}; \\ \Phi_{k\ i} = f(I_{ex.\ i}) \end{cases}$$

where $\kappa_{t.c.}$ and T_{μ} are the amplification factor and the response time of the thyristor converter;

$u_{c.}$ is the gate voltage of the thyristor converter;

$R_{eq.}$ and $T_{eq.}$ are the active resistance equivalent and the response time equivalent of the anchor chain;

M and M_s are the motor torque and static resistance;

J_{Σ} is the total mass moment of inertia of the rolling stand drive;

$U_{c.ex.}$ and $U_{ex.}$ are the gate voltage and output voltage of the thyristor actuator;

$R_{ex.}$ is the active resistance of the excitation circuit;

$T_{ex.}$ and T_k are the response time of the excitation circuit and the eddy current circuit;

$\mathrm{p} = \dfrac{\mathrm{d}}{\mathrm{dt}}$ is the time differentiation operator (Laplace operator).

The hydraulic screwdown mechanism as a control object can be described by three linearized differential equations [22].

1. Equation of fluid flow rate in the hydraulic screwdown mechanism for small coordinate increment:

$$Q = S_{h.c.} \frac{dS_{\text{p.t.}}}{dt} + \frac{V_{\text{p.t.}}}{E} \frac{dP_{\text{h.c.}}}{dt} + rP_{\text{h.c.}},$$

where Q is the flow rate of the fluid incoming to the head end of the hydraulic cylinder;

$S_{p.t.}$ is the position of the hydraulic cylinder piston;

$S_{h.c.}$ is the area of the hydraulic cylinder piston;

$V_{p.t.}$ is the piston displacement in the initial position;

E is the volumetric modulus of elasticity of the hydraulic fluid;

$P_{h.c.}$ is the pressure in the head end;

r is the leakage factor provided the flow rate due to leakage is proportional to the pressure in the head end.

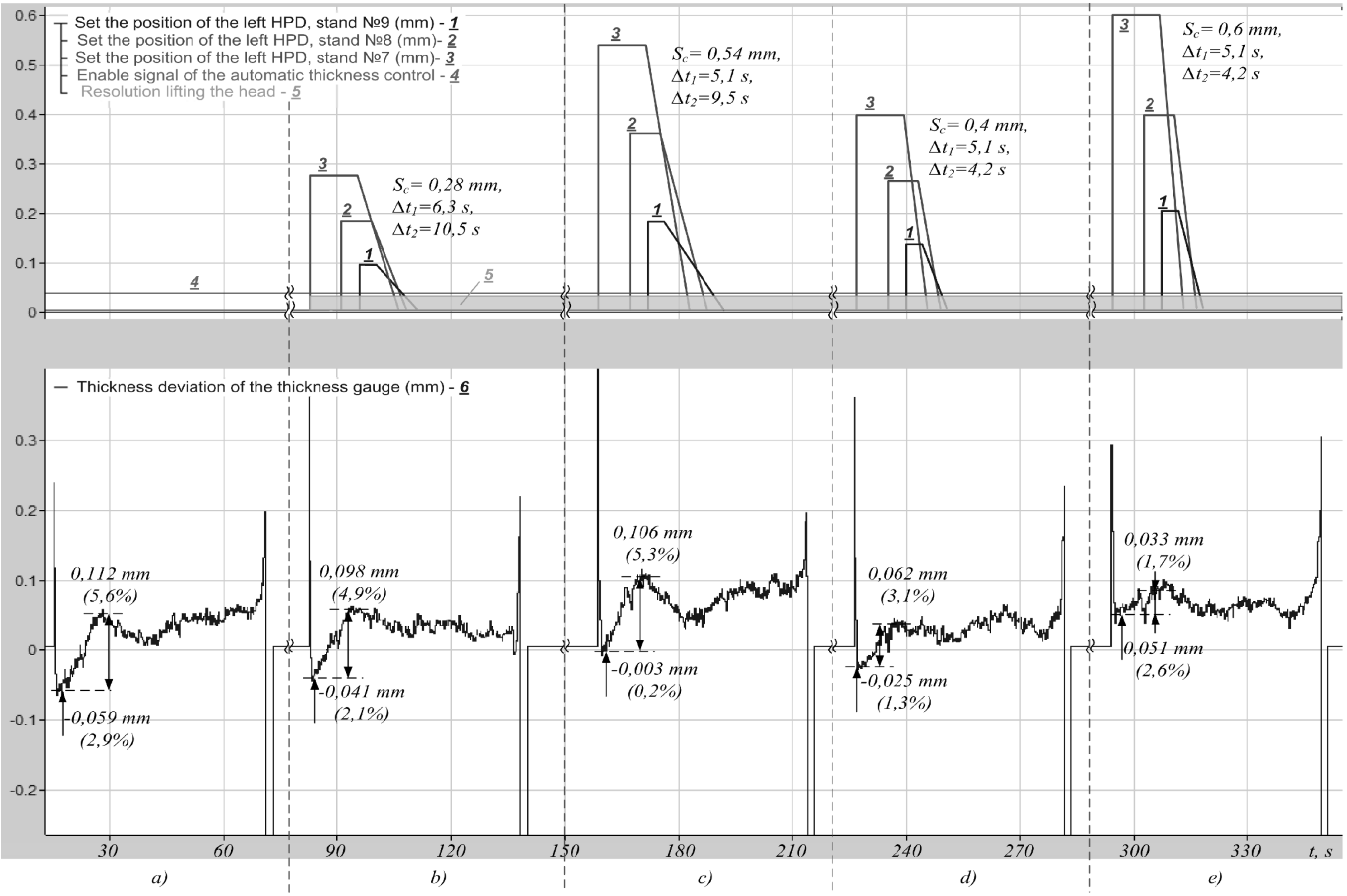

Fig. 2. Oscillograms when dealing with the correction of the head section thickness by rolling strips of 2 mm

2. Equation describing forces relationship in the rolling stand:

$$P_{h.c.}S_{\text{h.c.}} = P + m\frac{d^2S_{\text{p.t.}}}{dt^2} + b\frac{dS_{\text{p.t.}}}{dt},$$

where P is the total rolling pressure;

m is the weight of mechanical parts of the rolling stand moving with the hydraulic cylinder as well as the weight of the fluid in the pipe line from the battery to the hydraulic cylinder modified to the piston area;

b is the viscous friction factor determining the friction magnitude proportional to the displacement rate of the hydraulic screwdown mechanism and arising in the points of contact between the roll carriages and the bed shear of the rolling stand as well as between the hydraulic cylinder walls and the piston.

3. Linearized equation of the servo valve for small coordinate increment:

$$T_{s.v.}\frac{dQ}{dt} + Q = k_{s.v.}u_{s.v.} - k_{\text{f.c.}}P,$$

where $T_{s.v}$ is the response time of the servo valve;

$u_{s.v}$ is the control voltage (voltage on the input of the amplifier determining the control current in the electromagnetic coil of the servo valve);

$k_{\text{s.v}} = \frac{\text{d}Q}{du_{\text{s.v}}}$ is the flow rate factor of the servo valve constant almost in any voltage variation range;

$k_{f.c} = \left(\frac{\text{d}Q}{dm}\right)_0$ is the rigidity rate of the servo valve flow characteristic when the initial pressure in the head end is P_0.

The position control system of the hydraulic screwdown mechanism is equipped with a proportional action regulator. The hydraulic screwdown mechanisms are controlled by means of the automatic strip thickness control system developed on the principle of indirect thickness control on the basis of Golovin-Sims equation:

$$H_{i+1} = d_{i+1} + \frac{P_{i+1}}{K_{i+1}},$$

where d_{i+1} is the value of roll gap;

P_{i+1} is metal pressure on the rolls;

K_{i+1} is the modulus of rigidity of the rolling stand.

The processed strip as a control object can be described by the following equations [23]:

$$\begin{cases} \sigma_i = \dfrac{E_{st.}}{pL}(V'_{st\ i+1} - V_{st\ i} + V_{l.\ i}) + \sigma_{0\ i}; \\ V_i = V_{r.i}(1 + S_{0\ i} + \kappa_{s\ i}\ \sigma_i); \\ V'_{i+1} = V_{r.\ i+1}(1 + S_{0\ i+1} + \kappa_{s\ i+1}\ \sigma_i)\dfrac{H_{i+1}}{H_i}; \\ V_{l.\ i} = \dfrac{2r_{l.\ i}^{\ 2}}{L}\omega_i \sin 2\beta_i \end{cases}$$

where σ_i is the specific tension of rolled metal in the *i*-th interstand space;

$E_{st.}$ is the elastic modulus of rolled metal;

$V_{st.\ i}$ is the strip delivery speed from the previous rolling stand of the *i*-th interstand space;

$V'_{st.\ i+1}$ is the strip entrance speed into the successive rolling stand of the *i*-th interstand space;

$\sigma_{0\ i}$ is the initial value of specific tension of rolled metal in the *i*-th interstand space;

$V_{r.\ i}$, $V_{r.\ i+1}$ are linear speeds of roll rotation of the *i*-th and (*i+1*)-th rolling stand respectively;

$\kappa_{s\ i}$ is the interaction factor between the values of forward creep and front specific tension for the *i*-th rolling stand;

$\kappa_{s\ i+1}$ is the interaction factor between the values of forward creep and back specific tension for the (*i+1*)-th rolling stand;

$S_{0\ i}$, $S_{0\ i+1}$ are the values of forward creep for the *i*-th and the (*i+1*)-th rolling stands respectively;

H_i, H_{i+1} is the thickness of rolled metal at the outlet of the *i*-th and the (*i+1*)- th rolling stand respectively;

$V_{l.\ i}$ is the linear speed of the roll movement of the *i*-th looper.

Dresden formula is used to calculate the forward creep during rolling in the stand rolls, it can be expressed as:

$$S_{0\ i+1} = \frac{1}{4}\left(\frac{H_i}{H_{i+1}} - 1\right)\left(1 - \frac{1}{\mu}\sqrt{\frac{H_i - H_{i+1}}{2D_{i+1}}} + \frac{B(\sigma_{i+1} - \sigma_i)}{2P_{i+1}\mu}\right)^2.$$

The equation offered by academician A.I. Tselikov can be used to calculate metal pressure on rolls [23]:

$$P_i = \frac{BX_iH_{i-1}}{2\mu_i}\left[\frac{1}{\varphi_i}\left(\frac{X_{i-1}}{X_i}\right)^{\varphi_i} e^{m_i} - \left(\frac{X_{i-1}}{X_i} - 1\right) - \frac{1}{\varphi_i}\right],$$

where $\varphi_i = \frac{H_{i-1}}{H_{i-1} + H_i}$, $X_{i-1} = 1{,}15\sigma_{s\ i-1} - \sigma_{i-1}$, $X_i = 1{,}15\sigma_{s\ i} - \sigma_i$;

$\sigma_{s\ i-1}$, $\sigma_{s\ i}$ are yield points of metal strip before and after reduction in the stand;

μ_i is the friction factor between the working face of rolls and rolled metal;

$m_i = \frac{2\mu_i\ l_i}{H_{i-1} + H_i}$ – factor.

As a result of mathematical description of the electromechanical system “stand electric drive – hydraulic screwdown mechanism” the research group developed a structural diagram given in fig. 3.

The validity of the developed mathematical model was proved by comparison of transient processes of the main electric drive coordinates in the mode of roll gap decrease on the strip obtained by modeling and by oscillographic testing on the mill. Percentage error of the compared figures in the representative points does not exceed 7 %, which is quite acceptable for complex system modeling.

The developed mathematical model was used to study the main dynamic modes of electromechanical systems of seven rolling mills of the finishing train of 2000 rolling mill for measuring of the following parameters:

– additional correction value on the strip head section S_c;

– time of constant correction value Δt_1;

– time of correction decrease to zero Δt_2.

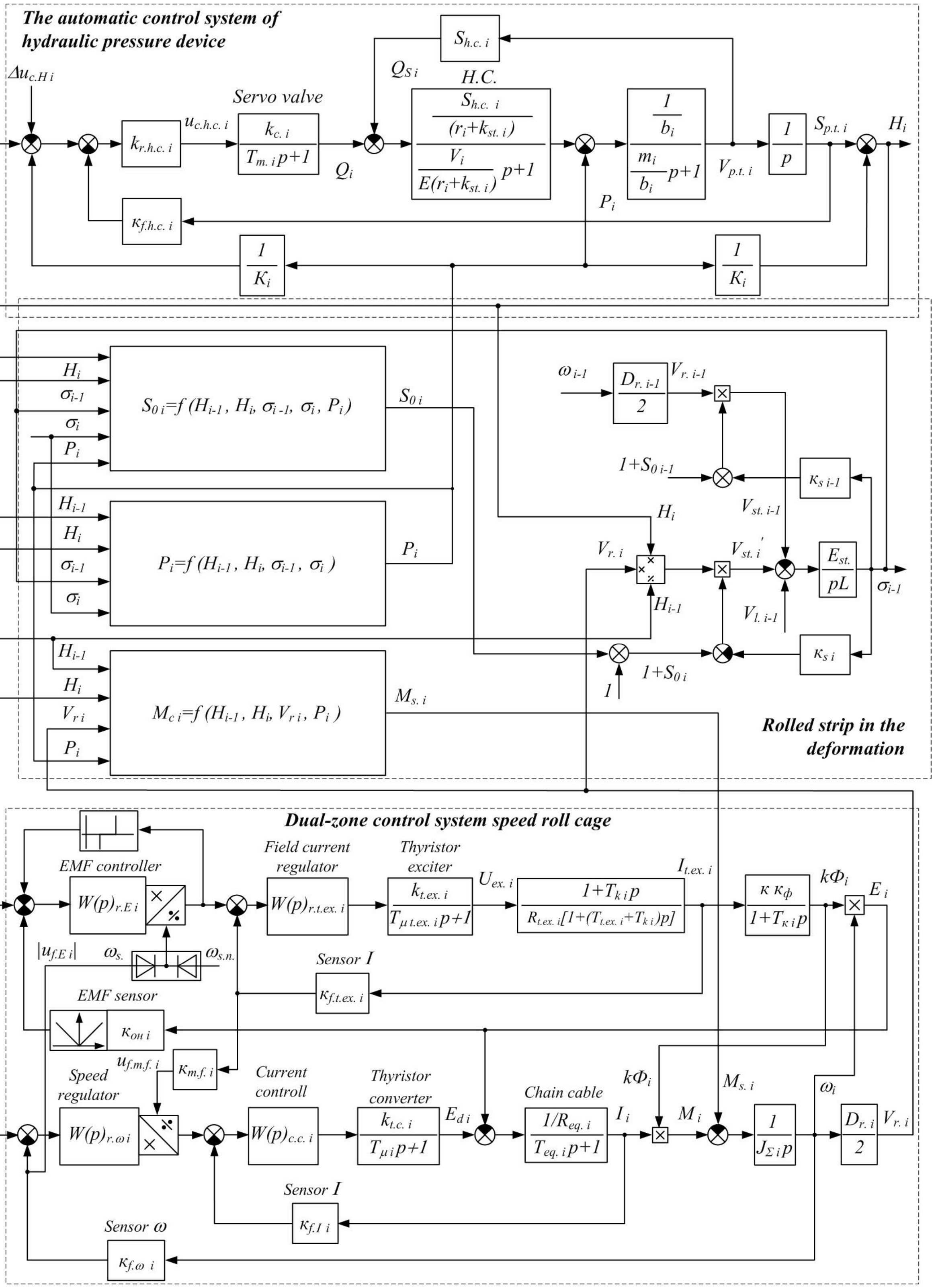

Fig. 3. Structural diagram of the mathematical model “stand electric drive – hydraulic screwdown mechanism”

Real variables of various strips were used as source data.

Calculated curves of thickness change ΔH_i with the change of roll gap (time Δt_2) are given in fig. 4 as an example.

Simulation data made it possible to determine the optimal control parameters on the strip head section (assumption 4 fig. 4) providing the least strip thickness deviation ΔH_i=0,6 %. Besides, the analysis of fig. 4 shows that selection of wrong adjustment parameters on the strip head section may result in thickness deviation (curve 6 fig. 4) comparable with deviations that would result if no adjustments were made (curve 1 fig. 4).

The results of investigations on the basis of the mathematical model allowed the authors to determine the control parameters of the roll gap providing the least thickness deviation of the strip head section. The varia bles for stands № 7–10 are given in the table 1. The minimum thickness deviation is less than 1 % (tolerances ±3,5 %).

The result of rolling of the first strips in the rolling mill proved that the selected parameters of roll gap adjustment can be considered optimum ones and can be recommended for advanced automatic strip thickness control of the mill [24–25]. Implementation of thickness control algorithm with the calculated optimum parameters of roll gap adjustment results in reduction of thickness deviation.

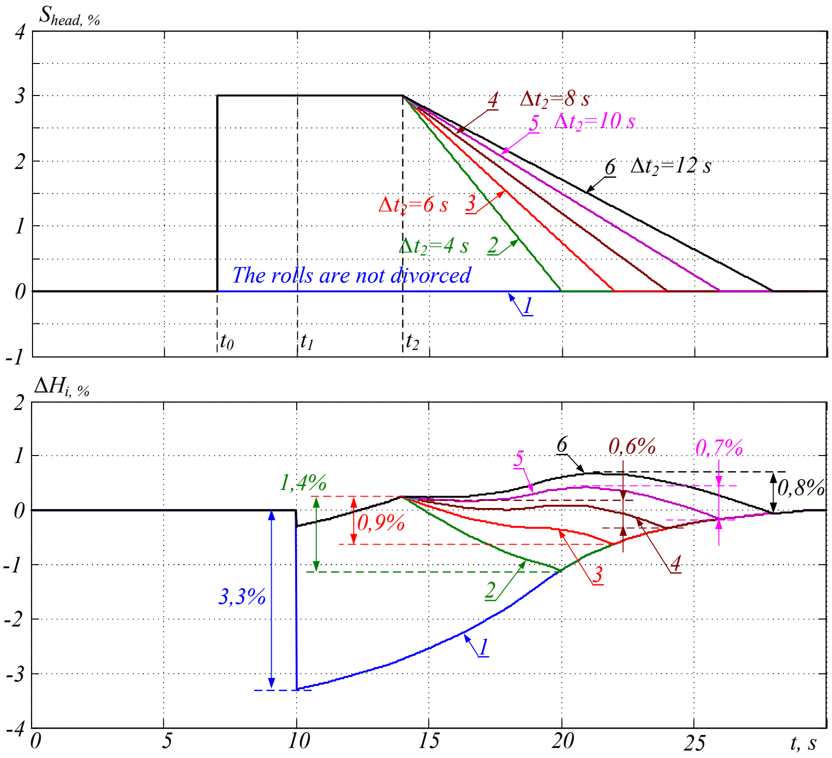

Fig. 4. Results of thickness deviation modeling for strip head section

Table 1

Correction parameters thickness of the cerebral part of the band

Stand	The thickness/ the correction	> 2 mm	2–4 mm	4–8 mm	8–12 mm	> 12 mm
№7	S_c, mm	0,6	0,5	0,9	0,75	0,4
	Δt_1, s	4	5	4	9	7
	Δt_2, s	6	3	5	8	8
№8	S_c, mm	0,4	0,4	0,7	0,5	0,3
	Δt_1, s	3	4	3	9	7
	Δt_2, s	6	5	5	8	8
№9	S_c, mm	0,2	0,4	0,5	0,3	0,3
	Δt_1, s	2	4	2,5	9	7
	Δt_2, s	6	5	5	8	8
№10	S_c, mm	0,15	0,2	0,3	0,2	0,3
	Δt_1, s	1	3	4	9	6
	Δt_2, s	6	5	5	8	8
№11	S_c, mm	0,1	0,1	0,2	0,1	0,2
	Δt_1, s	2	3	4	9	6
	Δt_2, s	5	5	5	8	9

Conclusions

1. The authors proved that it is necessary to study the rolling process with various control parameters of the strip head section and this study should be carried out using mathematical simulation methods.

2. The developed dynamic mathematical model of the system “stand electric drive – hydraulic screwdown mechanism” makes it possible to apply the suggested method of thickness control for the strip head section.

3. As a result of the research work the authors determined the optimum roll gap control parameters for the strip head section rolling and proved that these parameters provided the minimum thickness deviation.

4. The dynamic mathematical model can be used to analyze dynamic modes and to set the rolling stand automatic electric drives as well as hydraulic screwdown mechanisms thus contributing to improvement of final product quality of wide strip rolling mills.

References

1. Shiljaev P.V., Golovin V.V., Karandaev A.S., Hramshin V.R. Modernization Experience Thyristor Broadband of Hot Rolling Mill, *Trudy II Vserossijskoj nauchno-tehnicheskoj konferencii s mezhdunarodnym uchastiem «Problemy elektrotehniki, elektrojenergetiki i elektrotehnologii» [Proceedings II All-Russian Conference with International Participation "Problems of Electrical Engineering, Electricity and Electrical"]*, Tolyatti, 2007, vol. 2, pp. 353–356.

2. Karandaev A.S., Hramshin V.R., Shemetova A.A., Golovin V.V., Shiljaev P.V., Judin A.Ju. Feasibility Study of the Reconstruction of Electric Mill 2000 with the Replacement of the Control System and the Preservation of the Power Unit, *Steel* [*Stal*], 2009, no.3, p. 95.

3. Hramshin V.R. Development and Introduction of the Automated Electric Drives and Control Systems of Technological Parameters of the Wide Strip Hot Rolling Mill, *Vestnik IGJeU* [*Journal ISPU*], 2012, no. 6 pp. 100–104.

4. Hramshin V.R. Improvement of Electric Drives and Control Systems of Technological Parameters of the Wide Strip Hot Rolling Mill with the Expansion of the Assortment of Strips [Sovershenstvovanie elektroprivodov i sistem regulirovanija tehnologicheskih parametrov shirokopolosnogo stana gorjachej prokatki pri rasshirenii sortamenta polos]. *Trudy VII mezhdunarodnoj (XVIII vserossijskoj) nauchno-tehnicheskoj tonferencii po avtomatizirovannomu jelektroprivodu [Proceedings of the VII International (XVIII All-Russian) Scientific and Technical Conference on Automated Electric]*, Ivanovo, ISPU, 2012, pp. 561–565.

5. Hramshin V.R., Karandaev A.S., Hramshin V.R., Andrjushin I.Ju., Petrjakov S.A. Improvement of Automatic Control Thickness Wide Hot Rolling Mill [Sovershenstvovanie sistemy avtomaticheskogo regulirovanija tolshhiny shirokopolosnogo stana gorjachej prokatki]. *Trudy VII mezhdunarodnoj (XVIII vserossijskoj) nauchno-tehnicheskoj tonferencii po avtomatizirovannomu jelektroprivodu [Proceedings of the VII International (XVIII All-Russian) Scientific and Technical Conference on Automated Electric]*, Ivanovo, ISPU, 2012, pp. 556–561.

6. Karandaev A.S., Hramshin V.R., Shiljaev P.V., Andrjushin I.Ju., Golovin V.V. A System of Mutual Control Tension and Thickness of Broadband Hot Rolling Mill [Sistema vzaimnogo regulirovanija natjazhenija i tolshhiny shirokopolosnogo stana gorjachej prokatki]. *Trudy V mezhdunarodnoj (XVI vserossijskoj) nauchno-tehnicheskoj tonferencii po avtomatizirovannomu jelektroprivodu [Proceedings of the V International (XVI All-Russian) Scientific and Technical Conference on Automated Electric]*, St. Petersburg, 2007, pp. 410–413.

7. Karandaev A.S., Osipov O.I., Hramshin V.R. High-Speed Automatic Tension Control and Loop Broadband Hot Rolling Mill [Bystrodejstvujushhaja sistema avtomaticheskogo regulirovanija natjazhenija i petli shirokopolosnogo stana gorjachej prokatki]. *Trudy IV mezhdunarodnoj (XV vserossijskoj) nauchno-tehnicheskoj konferencii po avtomatizirovannomu jelektroprivodu [Proceedings of the V International (XVI All-Russian) Scientific and Technical Conference on Automated Electric]*, Magnitogorsk, vol. 2, 2004, pp. 60–66.

8. Petrjakov S.A., Karandaev A.S., Hramshin V.R. The Basic Principles of the SART Continuous Hot Rolling Mill [Osnovnye principy postroenija SART nepreryvnogo stana gorjachej prokatki]. *Mezhvuzovskij sbornik nauchnyh trudov «Elektrotehnicheskie sistemy i kompleksy» [Interuniversity Collection of Scientific Papers "Electrical Systems and Complexes"]*, Magnitogorsk, MGTU, 2008, vol. 15, pp. 142–148.

9. Petrjakov S.A., Hramshin V.R. The Automatic Thickness Control Broadband Hot Rolling Mill [Sistema avtomaticheskogo regulirovanija tolshhiny shirokopolosnogo stana gorjachej prokatki]. *Trudy III Vserossijskoj nauchno-tehnicheskoj konferencii s mezhdunarodnym uchastiem "Eelektroprivod, elektrotehnologii i elektrooborudovanie predprijatij" [Proceedings III All-Russian Conference with International Participation "Electric, Electrical Technology and Electrical Companies"]*, Ufa, 2011, pp. 263–268.

10. Hramshin V.R., Petrjakov S.A., Karandaev A.S. Thickness Measurement in SART Broadband Hot Rolling Mill [Izmerenie tolshhiny v SART shirokopolosnogo stana gorjachej prokatki]. *Trudy 9-j Vserossijskoj nauchno-prakticheskoj konferencii studentov, aspirantov i specialistov "Energetiki i metallurgi nastojashhemu budushhemu Rossii" [Proceedings the 9th All-Russian Scientific and Practical Conference of Students and Professionals "Energy and Metallurgy Really the Future of Russia"]*, Magnitogorsk, 2008, pp. 63–65.

11. Hramshin V.R., Andrjushin I.Ju., Shiljaev P.V., Petrjakov S.A., Gostev A.N. New Engineering Designs in the Automatic Control System of Hot Rolling Mill 2000’s Thickness [Tehnicheskie reshenija v

sisteme avtomaticheskogo regulirovanija tolshhiny stana 2000 gorjachej prokatki]. *Izvestija vuzov. Elektromehanika*, 2011, no 4, pp. 41–45.

12. Hramshin V.R. System of Automatic Correction Speeds of Electric Drives Stands of the Broad-Strip Hot Rolling Mill, *Bulletin of South Ural State University. Series "Power Engineering"*, 2012, no. 37 (296), pp. 60–67.

13. Galkin V.V., Petrjakov S.A., Karandaev A.S., Hramshin V.R. Automatic Correction of the Strip Head Section Thickness in a Hydraulic System of Automatic Control of Wide-Strip Hot Mill [Avtomaticheskaja korrekcija tolshhiny golovnogo uchastka polosy v gidravlicheskoj sisteme avtomaticheskogo regulirovanija tolshhiny shirokopolosnogo stana gorjachej prokatki], *Izvestija vuzov. Elektromehanika*, 2011, no 4, pp. 46–50.

14. Karandaev A.S., Radionov A.A., Hramshin V.R., Gostev A.N. Correction Method Capture Rates in a Continuous Strip Subgroup Stands Broadband Hot Rolling Mill [Sposob korrekcii skorostej zahvata polosy v nepreryvnoj podgruppe kletej shirokopolosnogo stana gorjachej prokatki]. *Mezhvuzovskij sbornik nauchnyh trudov «Elektrotehnicheskie sistemy i kompleksy» [Interuniversity Collection of Scientific Papers "Electrical Systems and Complexes"]*, Magnitogorsk, MGTU, 2012, vol. 20, pp. 141–149.

15. Hramshin V.R., Petrjakov S.A. Automatic Correction of the Thickness of the Strip Rolling Mill on Broadband [Avtomaticheskaja korrekcija tolshhiny polosy pri prokatke na shirokopolosnom prokatnom stane]. *Sbornik dokladom V-j Mezhdunarodnoj molodezhnoj nauchno-tehnicheskoj konferencii "Tinchurinskie chtenija" [Collection Report V-th International Youth Scientific Conference "Tinchurin Reading"]*, Kazan, 2010, pp. 65 – 66.

16. Hramshin V.R. Ways of Compensation Static Deviations Speed the Electric Drive of the Broad-Strip Hot Rolling Mill, *Electrical Engineering*, 2013, no. 4, pp. 48–55.

17. Patent 117329 RU, B 21 B 37/48. Device for Correcting the Thickness of the Head Section Strip Finishing Mill Broadband Hot Rolling Mill [Ustrojstvo dlja korrekcii tolshhiny golovnogo uchastka polosy v chistovoj kleti shirokopolosnogo stana gorjachej prokatki], Hramshin V.R., Karandaev A.S., Petrjakov S.A., Galkin V.V., Hramshin R.R., Filed: March 05, 2012; Date of Patent: June 27, 2012.

18. Hramshin V.R., Karandaev A.S., Petrjakov S.A. Removal of the Head Portion Gage Strip Hot Rolling Mill [Ustranenie raznotolshhinnosti golovnogo uchastka polosy na stane gorjachej prokatki]. *Mezhvuzovskij sbornik nauchnyh trudov «Elektrotehnicheskie sistemy i kompleksy» [Interuniversity Collection of Scientific Papers "Electrical Systems and Complexes"]*, Magnitogorsk, MGTU, 2011, vol. 19, pp. 159–163.

19. Karandaev A.S., Hramshin V.R., Galkin V.V., Lukin A.A. Mathematical Modelling of Thyristor Drive with Switched Structure [Matematicheskoe modelirovanie tiristornogo jelektroprivoda s perekljuchajushhejsja strukturoj]. *Izvestija vuzov. Elektromehanika*., 2010, no. 3, pp. 47–53.

20. Hramshin V.R., Lukin A.A. Development of a Two-Zone Thyristor Speed Control with Improved Performance [Razrabotka tiristornyh jelektroprivodov s dvuhzonnym regulirovaniem skorosti s uluchshennymi jenergeticheskimi pokazateljami]. *Sbornik dokladom V-j Mezhdunarodnoj molodezhnoj nauchno-tehnicheskoj konferencii "Tinchurinskie chtenija" [Collection Report V-th International Youth Scientific Conference "Tinchurin Reading"]*, Kazan, 2010, pp. 72–73.

21. Karandaev A.S., Hramshin V.R., Lukin A.A., Shurygina G.V., Golovin V.V. Experimental Researches of Two-Zonal Speed Control Thyristor Electric Drives with Improved Energy Characteristics [Eksperimentalnye issledovanija tiristornyh jelektroprivodov s dvuhzonnym regulirovaniem skorosti s uluchshennymi jenergeticheskimi harakteristikami]. *Bulletin of South Ural State University. Series Power Engineering*, 2010, no. 14, pp. 67–72.

22. Karandaev A.S., Hramshin V.R., Petrjakov S.A. The Servo-Mechanism of Automatic Control Strip Gage of the Hot-Rolling Mill [Sledjashhaja sistema avtomaticheskogo regulirovanija tolshhiny polosy stana gorjachej prokatki]. *Vestnik MGTU*. [*Vestnik MGTU*]. Magnitogorsk, MGTU, 2011, no. 3, pp. 25–29.

23. Karandaev A.S., Hramshin V.R., Andrjushin A.Ju., Golovin V.V., Shiljaev P.V. Mathematical Modeling of Interconnected Electromechanical System of Stand Interspace of Hot-Strip Rolling Mills [Matematicheskoe modelirovanie vzaimosvjazannyh jelektromehanicheskih sistem mezhkletevogo promezhutka shirokopolosnogo stana gorjachej prokatki]. *Izvestija vuzov. Elektromehanika*, 2009, no. 1, pp. 12–20.

24. Karandaev A.S., Radionov A.A., Hramshin V.R., Andrjushin I.Ju., Gostev A.N. Improvement of Automatic Control Thickness Wide Hot Rolling Mill [Soglasovanie skorostnyh rezhimov jelektroprivodov kletej nepreryvnoj gruppy prokatnogo stana]. *Vestnik IGJeU* [*Journal ISPU*], 2013, no. 1, pp. 98–103.

25. Karandaev A.S., Hramshin V.R., Andrjushin I.Ju., Golovin V.V., Petrjakov S.A. New Technical Solutions in Electric Drives and Control Systems of Technological Parameters of Hot Rolling Mills [Novye tehnicheskie reshenija v jelektroprivodah i sistemah regulirovanija tehnologicheskih parametrov stanov gorjachej prokatki]. *Izvestija TulGU. Tehnicheskie nauki* [*Proceedings of the TSU. Engineering*], 2010, no. 3, vol. 2, pp. 34–40.

УДК 621.313.2

ИССЛЕДОВАНИЕ СИСТЕМЫ АВТОМАТИЧЕСКОЙ КОРРЕКЦИИ ТОЛЩИНЫ ПОЛОСЫ НА ШИРОКОПОЛОСНОМ СТАНЕ ГОРЯЧЕЙ ПРОКАТКИ

В.Р. Храмшин, А.С. Карандаев, А.А. Радионов, Р.Р. Храмшин

Выполнена модернизация системы автоматического регулирования толщины (САРТ) стана 2000 ОАО «Магнитогорский металлургический комбинат» (ОАО «ММК»). Дано краткое описание внедренной САРТ, выполненной на базе гидравлических нажимных устройств (НУ). Проведенные экспериментальные исследования выявили недопустимые отклонения толщины на головном участке полосы, достигающие 10 % в сторону уменьшения. Это приводит к возникновению разнотолщинного головного участка полосы длиной 40–50 м на выходе стана. Предложен способ коррекции толщины головного участка, осуществляемый за счет разведения валков клетей перед захватом полосы и последующего их сведения до заданного положения за счет перемещения гидравлических НУ во время прокатки. Рассмотрен алгоритм изменения межвалкового зазора. Обоснована необходимость оптимальной настройки времени удержания максимального разведения валков и времени уменьшения коррекции до нуля. Разработана математическая модель системы «электропривод клети – гидравлический привод нажимных устройств» с учетом взаимосвязи названных приводов через прокатываемый металл. Математическая модель электропривода клети построена в системе двухзонного регулирования скорости. Гидравлические НУ описываются линеаризованными дифференциальными уравнениями расхода жидкости, сервоклапана для малых приращений координат и соотношения усилий в прокатной клети. Модель включает систему дифференциальных уравнений, описывающих прокатываемую полосу как объект управления, а также математическое описание системы автоматического регулирования положения НУ. Дано подтверждение адекватности разработанной модели исследуемому объекту. Выполнено исследование динамических режимов при изменениях параметров коррекции межвалкового зазора. Определены оптимальные параметры коррекции, при которых обеспечивается наименьшее отклонение толщины головного участка. Прокатка на стане первых партий полос подтвердила эффективность разработанного способа компенсации разнотолщинности головного участка.

Ключевые слова: стан горячей прокатки, толщина полосы, отклонения, система регулирования, математическая модель, исследование, эксперимент.

Литература

1. Опыт модернизации тиристорных электроприводов широкополосного стана горячей прокатки / П.В. Шиляев, В.В. Головин, А.С. Карандаев, В.Р. Храмшин // Проблемы электротехники, электроэнергетики и электротехнологии: Тр. II Всерос. науч.-техн. конф. с междунар. участием. – Тольятти, 2007. – Ч. 2. – С. 353–356.
2. Технико-экономическое обоснование реконструкции электроприводов стана 2000 с заменой системы управления и сохранением силовой части / А.С. Карандаев, В.Р. Храмшин, А.А. Шеметова и др. // Сталь. – 2009. – № 3. – С. 95.
3. Храмшин, В.Р. Разработка и внедрение автоматизированных электроприводов и систем регулирования технологических параметров широкополосного стана горячей прокатки / В.Р. Храмшин // Вестник ИГЭУ. – 2012. – № 6. – С. 100–104.
4. Храмшин, В.Р. Совершенствование электроприводов и систем регулирования технологических параметров широкополосного стана горячей прокатки при расширении сортамента полос / В.Р. Храмшин // VII Междунар. (XVII Всерос.) науч.-техн. конф. по автоматизированному электроприводу (АЭП-2012): сб. тр. – Иваново: ФГБОУ ВПО «ИГЭУ», 2012. – С. 561–565.
5. Совершенствование системы автоматического регулирования толщины широкополосного стана горячей прокатки / В.Р. Храмшин, А.С. Карандаев, Р.Р. Храмшин, С.А. Петряков // VII Междунар. (XVII Всерос.) науч.-техн. конф. по автоматизированному электроприводу (АЭП-2012): сб. тр. – Иваново: ФГБОУ ВПО «ИГЭУ», 2012. – С. 556–561.
6. Карандаев, А.С. Система взаимного регулирования натяжения и толщины широкополосного стана горячей прокатки / А.С. Карандаев, В.Р. Храмшин П.В. Шиляев и др. // V Междунар. (XVI Всерос.) конф. по автоматизированному электроприводу (АЭП-2007): сб. тр. – СПб., 2007. – С. 410–413.
7. Карандаев, А.С. Быстродействующая система автоматического регулирования натяжения и петли широкополосного стана горячей прокатки / А.С. Карандаев, О.И. Осипов, В.Р. Храмшин // IV Междунар. (XV Всерос.) конф. по автоматизированному электроприводу (АЭП-2004): сб. тр. – Магнитогорск, 2004. – Т. 2. – С. 60–66.
8. Петряков, С.А. Основные принципы построения САРТ непрерывного стана горячей прокатки / С.А. Петряков, А.С. Карандаев, В.Р. Храмшин // Электротехнические системы и комплексы: межвуз. сб. науч. тр. – Магнитогорск: МГТУ, 2008. – Вып. 15. – С. 142–148.
9. Петряков, С.А. Система автоматического регулирования толщины широкополосного стана горячей прокатки / С.А. Петряков, В.Р. Храмшин // Электропривод, электротехнологии и электрооборудование предприятий: сб. науч. тр. III Всерос. науч.-техн. конф. с международ. участием. – Уфа: ИД «Чурагул», 2011. – С. 263–268.

10. Храмшин, В.Р. Измерение толщины в САРТ широкополосного стана горячей прокатки / В.Р. Храмшин, С.А. Петряков, А.С. Карандаев // Энергетики и металлурги настоящему будущему России: Матер. 9-й Всерос. науч.-практ. конф. студ., аспирантов и спец. – Магнитогорск: МГТУ, 2008. – С. 63–65.

11. Технические решения в системе автоматического регулирования толщины стана 2000 горячей прокатки / В.Р. Храмшин, И.Ю. Андрюшин, П.В. Шиляев и др. // Известия вузов. Электромеханика. – 2011. – № 4. – С. 41–45.

12. Храмшин, В.Р. Система автоматической коррекции скоростей электроприводов клетей широкополосного стана горячей прокатки / В.Р. Храмшин // Вестник ЮУрГУ. Серия «Энергетика». – 2012. – Вып. 18. – № 37 (296). – С. 60–67.

13. Автоматическая коррекция толщины головного участка полосы в гидравлической системе автоматического регулирования толщины широкополосного стана горячей прокатки / В.В. Галкин, С.А. Петряков, А.С. Карандаев, В.Р. Храмшин // Известия вузов. Электромеханика. – 2011. – № 4. – С. 46–50.

14. Способ коррекции скоростей захвата полосы в непрерывной подгруппе клетей широкополосного стана горячей прокатки / А.С. Карандаев, А.А. Радионов, В.Р. Храмшин, А.Н. Гостев // Электротехнические системы и комплексы: Межвуз. сб. науч. тр. – Магнитогорск: МГТУ, 2012. – Вып. 20. – С. 141–149.

15. Храмшин, В.Р. Автоматическая коррекция толщины полосы при прокатке на широкополосном прокатном стане / В.Р. Храмшин, С.А. Петряков //Тинчуринские чтения: матер. докл. V-й Междунар. мол. науч.-техн. конф. – Казань: КГЭУ, 2010. – С. 65–66.

16. Храмшин, В.Р. Способы компенсации статических отклонений скорости электроприводов клетей широкополосного стана горячей прокатки / В.Р. Храмшин // Электротехника. – 2013. – № 4. – С. 48–55.

17. Патент РФ на полезную модель 117329, МПК7 В 21 В 37/48. Устройство для коррекции толщины головного участка полосы в чистовой клети широкополосного стана горячей прокатки / В.Р. Храмшин, А.С. Карандаев, С.А. Петряков, В.В. Галкин, Р.Р. Храмшин // БИМП – 2012. – № 18. – С. 38.

18. Храмшин, В.Р. Устранение разнотолщинности головного участка полосы на стане горячей прокатки / В.Р. Храмшин, А.С. Карандаев, С.А. Петряков // Электротехнические системы и комплексы: межвуз. сб. науч. тр. – Магнитогорск: МГТУ, 2011. – Вып. 19. – С. 159–163.

19. Математическое моделирование тиристорного электропривода с переключающейся структурой / А.С. Карандаев, В.Р. Храмшин, В.В. Галкин, А.А. Лукин // Известия вузов. Электромеханика. – 2010. – № 3. – С. 47–53.

20. Храмшин, В.Р. Разработка тиристорных электроприводов с двухзонным регулированием скорости с улучшенными энергетическими показателями / В.Р. Храмшин, А.А. Лукин // Тинчуринские чтения: матер. докл. V-й Междунар. мол. науч.-техн. конф. – Казань: КГЭУ, 2010. – С. 72–73.

21. Карандаев, А.С. Экспериментальные исследования тиристорных электроприводов с двухзонным регулированием скорости с улучшенными энергетическими характеристиками / А.С. Карандаев, В.Р. Храмшин, А.А. Лукин, Г.В. Шурыгина, В.В. Головин // Вестник ЮУрГУ. Серия «Энергетика». – 2010. – Вып. 13. – № 14(190). – С. 67–72.

22. Карандаев, А.С. Следящая система автоматического регулирования толщины полосы стана горячей прокатки / А.С. Карандаев, В.Р. Храмшин, С.А. Петряков // Вестник МГТУ. – Магнитогорск: МГТУ. – 2011. – №3. – С. 25–29.

23. Математическое моделирование взаимосвязанных электромеханических систем межклетевого промежутка широкополосного стана горячей прокатки / А.С. Карандаев, В.Р. Храмшин, А.Ю. Андрюшин и др. // Известия вузов. Электромеханика. – 2009. – № 1. – С. 12–20.

24. Согласование скоростных режимов электроприводов клетей непрерывной группы прокатного стана / А.С. Карандаев, А.А. Радионов, В.Р. Храмшин и др. //Вестник ИГЭУ. – 2013. – № 1. – С. 98–103.

25. Новые технические решения в электроприводах и системах регулирования технологических параметров станов горячей прокатки / А.С. Карандаев, В.Р. Храмшин, И.Ю. Андрюшин, В.В. Головин, С.А. Петряков // Известия ТулГУ. Технические науки. – Тула: ТулГУ, 2010. – Вып. 3. – Ч. 2. – С. 34–40.

Храмшин Вадим Рифхатович, кандидат технических наук, доцент, доцент кафедры электротехники и электротехнических систем, МГТУ им. Г.И. Носова, г. Магнитогорск, тел. 8 (3519) 29-84-16, E-mail: hvr_mgn@mail.ru

Карандаев Александр Сергеевич, главный научный сотрудник кафедры теоретических основ электротехники, Южно-Уральский государственный университет, г. Челябинск, доктор технических наук, профессор, тел. 8 (3519) 29-84-16; E-mail: askaran@mail.ru

Радионов Андрей Александрович, доктор технических наук, профессор, декан энергетического факультета, заведующий кафедрой теоретических основ электротехники, Южно-Уральский государственный университет, г. Челябинск, тел. 8 (351) 272-31-41, E-mail: radionovaa@susu.ac.ru

Храмшин Рифхат Рамазанович, доцент кафедры электротехники и электротехнических систем МГТУ им. Г.И. Носова, г. Магнитогорск, кандидат технических наук, доцент, тел. 8 (3519) 29-84-16, E-mail: hramshinrr@mail.ru

Поступила в редакцию 20.03.2013 г.