Автоматизированные системы управления технологическими процессами

DOI: 10.14529/ctcr160111

DEVELOPMENT OF AUTOMATIC CONTROL SYSTEM OF HOT-STRIP MILL PROCESS PARAMETERS

S.S. Voronin, *voronsot@mail.ru*,
V.R. Gasiyarov, *gasiiarovvr@susu.ac.ru*,
E.A. Maklakova, *karyakina-katya@yandex.ru*,
A.A. Radionov, *radionovaa@rambler.ru*
South Ural State University, Chelyabinsk, Russian Federation

It is observed that the contemporary trend of rolling development is widening of hot-strip mills assortment because of ultrathin hot-rolled strips production instead of cold-rolled ones. The advisability of the automatic control system of process parameters (such as tension, gauge, and roll speed) update is demonstrated on the examples of wide-strip mills 2000 and 2500 at Magnitogorsk Iron & Steel Works. Control algorithms for electric drives speed rates are examined, which provide proportional position control of finishing rolling speed under control and perturbation actions with corrective action transmission against rolling direction. Corrected digital algorithms of tension dynamic control enabling longitudinal grow-back decreasing due to accuracy increase of looper electric drive torque and loop size in interstand space computation are presented. The streamlined structure of automatic control system of strip gage (ACSG). The system realizes control method on base of indirect control with sensor values averaging over a specified period of time combined with direct control following exit gage signal and external correction providing perturbation actions compensation and draft redistribution in finishing trains. The developed system of automatic head end gage correction by moving rollers apart before strip enters mill with their subsequent return to specified position for main strip end rolling is demonstrated. The results of improved ACSG application investigations on operating rolling mill are presented. The method and the system of interactive tension and strip gage control are proved and examined whereby automatic correction of hydraulic roll screwdown position of the previous stand under perturbation and control actions caused by change of looper or roll screwdown of the next stand positions is implemented. The results of research and commercialization of the developed systems confirm technical-and-economic efficiency provided with reduction in input of materials, improvement in the quality of production and steadiness of the processing.

Keywords: hot-strip mill, continuous train, process parameters, automatic control system, development, technical decisions, application investigations, commercialization.

Introduction

The rolling mills automation level defines the accuracy of process parameters control that is the main factor affecting the quality and competitiveness of iron and steel works product.

Research conducted by experts from International Iron and Steel Institute (IISI), (since 2008 – World Steel Association, Worldsteel) allowed to state the main requirement which should be met in XXI century that is high quality, low cost and small-lot steel delivery in a short space of time [1].

In two recent decades, there is a growing demand for thin hot-rolled 0.8–1.2 mm strip being a final market product that is not to be treated in cold position. Nevertheless, it is objectively held that conventional highly productive mill guarantees good quality when the gauge of the plate is not less than 1.5 mm. While attempting to produce strip plate thinner than named, there are technical and technological difficulties connected with overranging the permissible speed and temperature [2].

It is evident that full compatibility of quality characteristics for hot-rolled and cold-rolled strips with the same gauge is reachless. However, for the significant part of assortment it is enough to provide the necessary geometrical dimensions and their high-precision distribution along the length.

Historically, the domestic steel industry produced all hot-rolled strip products on highly productive hot-strip mills (HSM) that changed several generations in their improvement. Such mills at Magnitogorsk Iron & Steel Works are mills 2000 and 2500 originally designed for producing strips made of commercial steel with a gauge from 4 to 16 mm with production output about 4 million tons per year.

A similar situation exists at the other steel works where the second and the third generation mills are used. Thereby, the market needs in thin hot-rolled strip must be provided with these very mills.

Automation level of domestic HSM is high enough, but to produce the strips of broadened assortment it needs in improving the main automatic control systems of such process parameters as loop tension and height (ACST&H), strip gage (ACSG) and speed rate control (SSRC). In such case, a conceptually new problem is to provide interactive control of these parameters in steady-state and dynamic conditions in the same way that it is realized on cold-rolled mills.

The main HSM process unit defining capacity and product quality is continuous (finishing) train. The continuous train of mill 2000 consists of seven four-high stands (Fig. 1). Besides, complex includes hydraulic roll screwdowns as a part of ACSG, and driving loopers in interstand spaces that really work as tension sensors. The quantity of stands depends on rolling strip section: thin strips are rolled with all finishing stands, and thicker strips with five or six ones. The equipment configuration of finishing mill 2500 group is similar to shown one. The difference is that only four last stands are supplied with HRS.

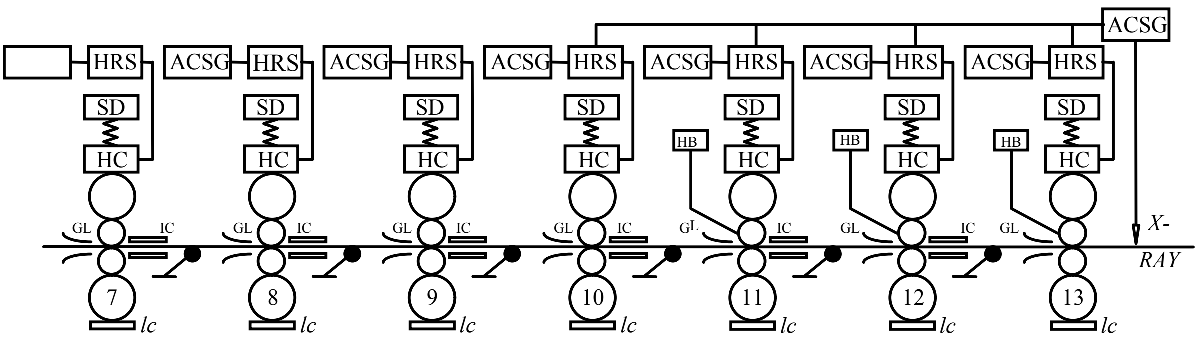


Fig. 1. Function chart of improved ACSG of mill 2000:
HRS – hydraulic roll screwdown; SD – electric screwdown driver control system; GL – guide ledges control system; HB – control system for work rolls hydraulic bending; IC – interstand strip cooling system; HC – hydraulic cylinder of stand; *lc* – load-cell strain gauge; *X-RAY* – gaugemeter

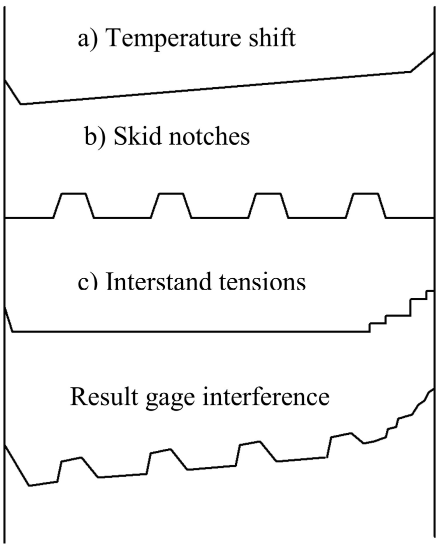


Fig. 2. Result strip gage interference and its components

During hot rolling, the main perturbations affecting thickness deviation (gage interference) are changes of temperature, chemical and mechanical heterogeneity of strips, changes of interstand tensions, roll speed changes, backup and working roll bounce, roll wear, etc. Simultaneous action of all or most of perturbations gives a very complicated picture of thickness deviation. However, the result gage interference of hot-rolled strip can be presented very tentatively as a sum of thickness changes caused by temperature wedge, skid notches and interstand tensions fluctuations (Fig. 2) [3].

To decrease the influence of each named factor on strip gage interference, complex of technical solutions was developed and implemented on mills 2000 and 2500 at Magnitogorsk Iron & Steel Works. The major developments are given below.

1. Development of the speed rate control system

The distinction of thin strips rolling is a tension strong effect on the thickness that usually takes place in cold-rolling mills. In HSM finishing group, tension control in conjunction with ACST&H is implemented due to speed control system of interrelated stands electric drivers. In fact, it is the system of automatic speed matching under combined rolling.

To increase tension control accuracy, a system and algorithm of cascade speed correction of previous finishing stand electric drivers [4, 5] are developed. The gist of the matter is in correction actions summation and transmission against rolling direction. The last rolling stand is used as a supporting one according to constant strip speed requirements when emerging from the finishing group. Fig. 3 gives scheme of cascade design for Fx and Fx-1 stands where Fx is a supporting stand.

While correcting Fx stand speed during the rolling, the necessary condition is to keep preset strip tensions in all interstand spaces. For this purpose, the circuit transmitting percent actions of Fx stand speed changes to all the previous stands. These actions are transmitted both under manual intervention and under looper perturbation actions or roll gaps changes when rolling.

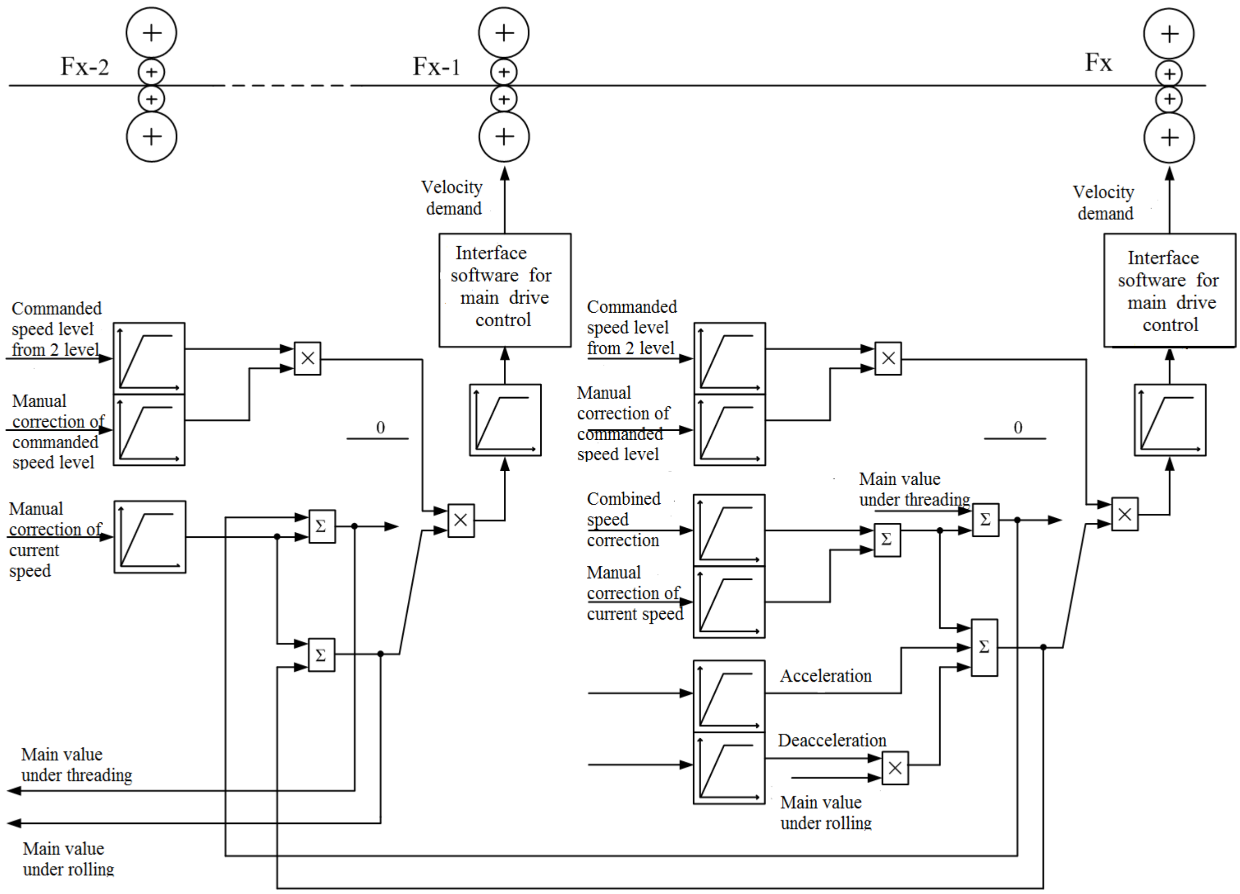


Fig. 3. Scheme of speed control system with corrective action transmission against rolling direction

The aim of such speed control method implementing is to increase the accuracy of the loop height setting and control in interstand space. For this purpose, the system of loop size control, which corrects the speed of stand before the looper, is developed (Fig. 4). Loop size controller effecting on speed setting equalizes the difference between the preset and real strip lengths. It allows to keep the loop size constant. The controller has proportional-plus-integral property. EMF of looper drive is used as a stabilizing feedforward of looper location correction circuit.

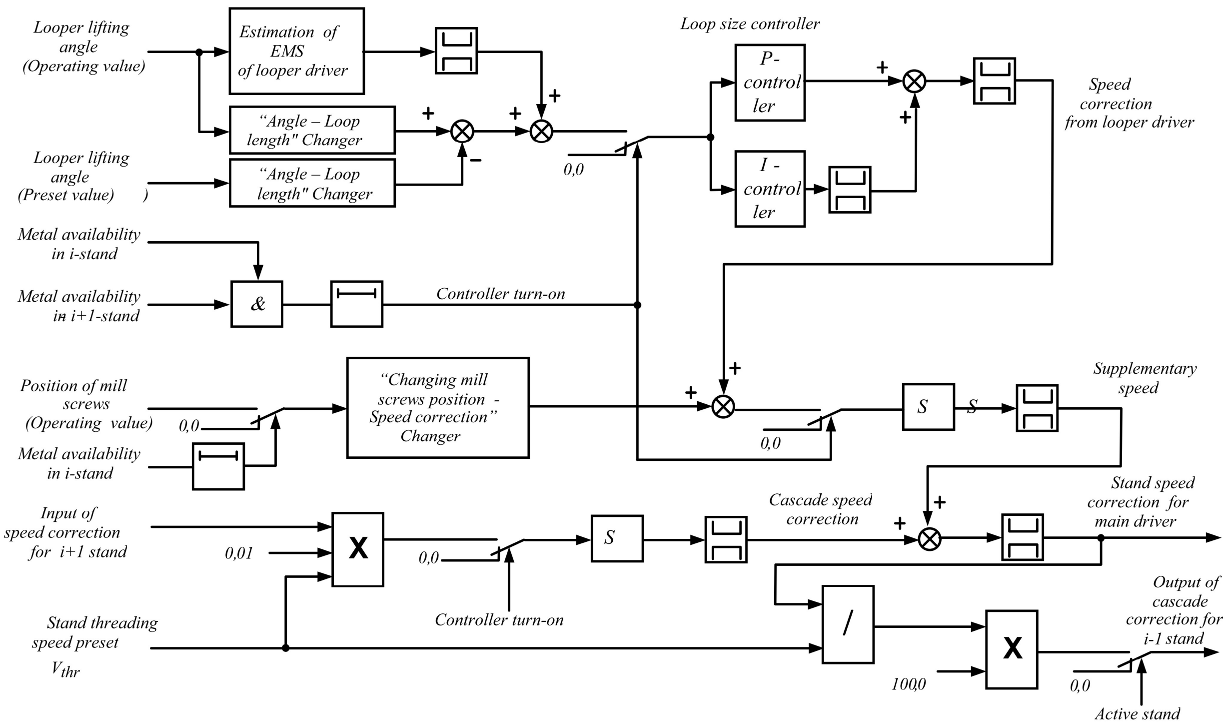


Fig. 4. System of loop size control

Controller setting is the height of metal loop h_{set} above the mill pass line (Fig. 5). The operating looper lifting angle according to preset loop height is calculated using the formula (the indications are on Fig. 5):

$$\beta_{set} = \arcsin\frac{h_{set} + d - r}{1}.$$

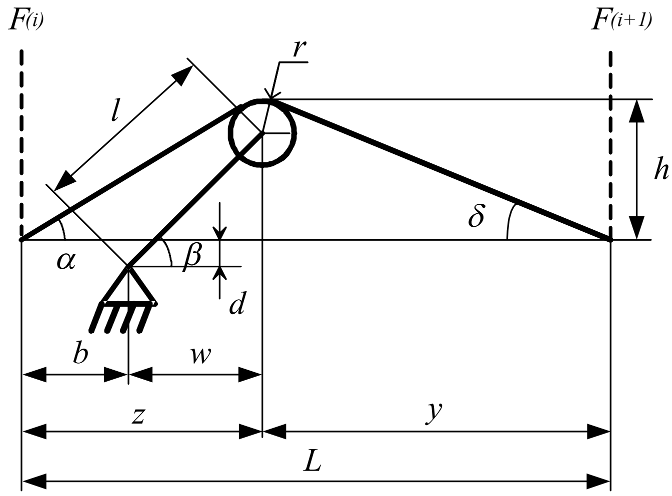


Fig. 5. Output scheme of looper mechanisms

Looper length is evaluated by formula: $X = \sqrt{h^2 + z^2} + \sqrt{h^2 + y^2}$.

Preset strip length in interstand space is calculated on base of preset loop height h_{set}:

$$X_{set} = \sqrt{h_{set}^2 + \left[b + l\cos\left(\arcsin\frac{h_{set} + d - r}{1}\right)\right]^2} + \sqrt{h_{set}^2 + \left\langle l - \left[b + l\cos\left(\arcsin\frac{h_{set} + d - r}{1}\right)\right]\right\rangle^2}.$$

In the system, operating (actual) looper lifting angle β_{Act} is used as feedback signal. Actual strip length is calculated from it:

$$X_{Act} = \sqrt{\left[\left(l\sin\beta_{Act}\right) - d + \mathrm{r}\right]^2 + \left[b + l\cos\beta_{Act}\right]^2} + \sqrt{\left[\left(l\sin\beta_{Act}\right) - d + \mathrm{r}\right]^2 + \left\langle L - \left[b + l\cos\beta_{Act}\right]\right\rangle^2},$$

where $h = l\sin\beta - d + r$; $z = b + l\cos\beta$; $y = L - z$.

The reviewed technical solutions are implemented in commercial operation in finishing mill 2500 group automatic process control system. Simatic S7-400 controllers and Simatic ET–200M remote input/output modules are used as base hardware, and herein interface channels PROFIBUS and Ethernet TCP/IP are used for communication. In this case, the changes made in speed control system refer only to industrial sequence control software and require no additional hardware including additional process parameters sensors.

The results of experimental studies of improved implemented SSRC are given in [6, 7]. Long-term operation confirmed its advantages consist in improved accuracy of rolling strip preset tension support.

2. Improvement of strip gage automatic control system

In ACSG of the most modern HSM strip gage is regulated in each stand output with indirect Sims-Golovin formula evaluation [1]. Furthermore, the output gage at the time of ACSG switching on is stored. Further, it is maintained up to the end of the lot or manual intervention. After that, the new value is stored. Output gage correction allows obtaining the preset lengthway gage strip. This correction is relatively “slow” because of transport lag.

The functional chart explaining ACSG design concept is given on Fig. 6. A setting of roll screwdown (RS) position can be conditionally divided in static correction signals responsible for required strip gage and dynamic correction signals responsible for gage stabilizing along the strip. Static correction signals are permanent for the whole lot of metal (if there is no manual intervention). Dynamic correction signals are calculated for each strip and nulled when the strip gets out of the stand.

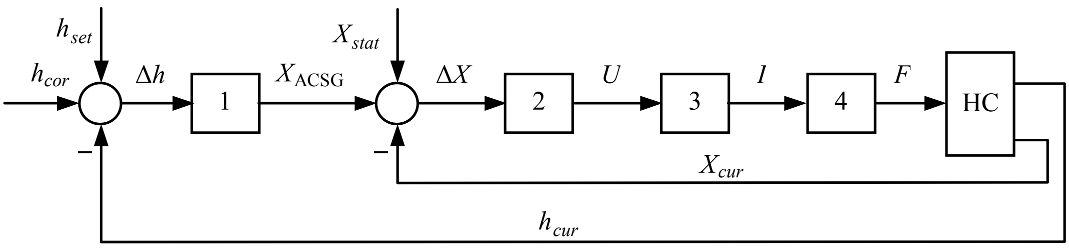


Fig. 6. Signals of ACSG assignment

Gage setting signal h_{set} at the stand output is added together with correction signal h_{cor} and compared with the current strip gage. Gage deviation Δh is fed to controller of dynamic correction 1 of ACSG position. Output signal X_{ACSG} of this controller is a task to remove RS for received gage deviation compensation. Then static setting X_{stat} of hydraulic RS position is added to the ACSG dynamic correction signal X_{ACSG} and compared with a current roll screwdown position X_{cur}. The value of roll screwdown position deviation ΔX is an input signal for hydraulic cylinder (HC) position controller 2. The following is a $U \sim I$ transducer 3 generating a signal for servovalve 4 which controls oil flow F in hydraulic cylinder.

3. Dynamic gage correction

The functional chart of dynamic correction system is given on Fig. 7 [8]. The input signal Δh of position controller is composed as following:

$$\Delta h = h_{set} + h_{gage} + h_{next} + h_{ext} - h_{cur}.$$

The set gage h_{set} is calculated when gage-stabilizing mode is on under the condition that metal is treaded into the next stand, i.e. the steady mode of rolling takes place.

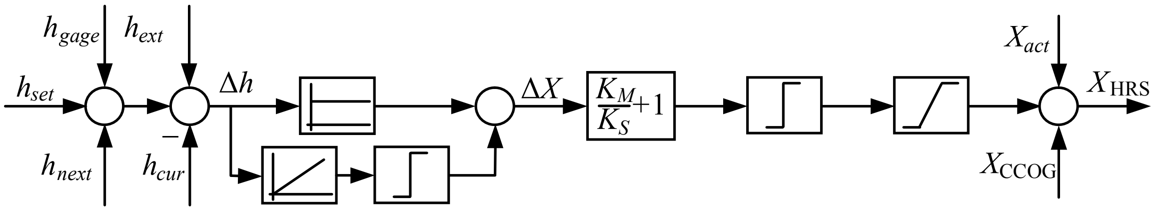


Fig. 7. Signals and structure of dynamic gage correction system

According to the developed algorithm, the position sensor readings and roll force are averaged in preset time (≈400 ms), and the strip gage at the stand output is calculated and stored as a setpoint. Then the following correction signals are added to the setpoint:

- h_{gage} – fine correction from output gage. It is an integrated value of gage deviation from set gage at the finishing group output;
- h_{next} – correction from the next stand. Its function is to reassign control to the previous stands when dynamic correction of this stand RS gets close to limit;
- h_{ext} – external correction. The possible corrections can be such as a compensation of oil film thickness in roll bearings, rolls thermal-compensation, roll ware compensation, forward correction, etc.

Feedback signal h_{cur} (the current strip gage at this stand output) is subtracted from the obtained sum. The obtained deviation Δh is entered into proportional-plus-integral position controller with the limited integral part.

The calculated output signal of dynamic correction X_{ACSG} is added to the static setting of RS position:

$$X_{\text{ACSG}} = K_p \Delta h + K_i \int (\Delta h dt) \cdot \left(\frac{K_M}{K_S} + 1 \right),$$

where K_p, K_i – coefficients of proportional and integral parts of controller; K_M, K_S – stiffness factors of metal and stand.

Thus, the hydraulic RS position setpoint is determined by a sum of static active (average) position, ACSG dynamic correction and coarse correction from output gage X_{CCOG}:

$$X_{\text{HRS}} = X_{act} + X_{\text{ACSG}} + X_{\text{CCOG}} .$$

Along with the presented technical solutions, the improved ACSG, which provides draft redistribution to finishing stands. It prevents the saturation of last stand RS position controller under large corrective signals coming from thickness gage [9]. It gives an opportunity to limit integral correction on the last stands and so to prevent gage control circuit cutting.

4. The results of the improved ACSG experimental investigations

Deviations of the thickness are shown on Fig. 8. These deviations are measured with output thickness gage set after the stand No.13 of the mill 2000 when this improved ACSG is working. Oscillograph trace is obtained during 4.7 mm thick strip rolling. Neither temperature wedge no definite skid notches are present. The strip grow-back on the main section is not more than 80 µm that is tolerance.

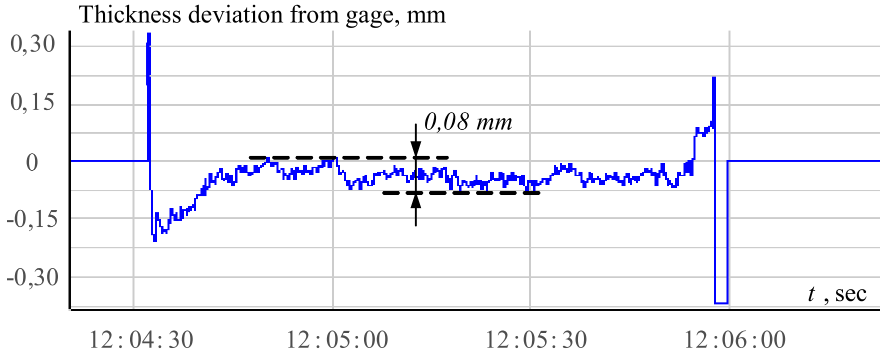


Fig. 8. Thickness deviations along the strip during the improved ACSG work

The experimental results prove that using of ACSG, in which the proposed technical solutions are implemented, makes it possible to annul the temperature wedge, to decrease amplitude of skid notches by factor of 1.8 and to reduce the length of grow-back sections. Generally, the system enables to reduce longitudinal grow-back and as a result, to enhance the quality of output product.

However, total exclusion of thickness variations caused by run-out of backup rolls is not fully succeeded. Use of low-frequency filter on the measuring unit output provides it with the features of relaxation circuit and adversely affects the ACSG ability to exclude perturbations like skid notches. Besides, Fig.8 shows decreasing thickness deviations in the course of strip head end rolling which is not typical for the other hot-rolling mills.

To exclude this type of grow-back, the method of parametric control of strip head end thickness by means of forward roll gap increase before the strip enters the stand with subsequent screwdown return to initial position for the main section rolling [10–12]. The functional chart of the control system implementing the method of rolling with roll gap automatic change (correction) in strip length function [13, 14].

For gap change parameters setting, the experiments for testing the strip rolling with different correction parameters in stands were carried out [15]. In addition, an influence of the roll gap change on strip thickness deviations was examined by means of mathematical modeling techniques [16]. As a result, averaged thickness correction parameters during head section rolling are founded for strips of different assortment.

On Fig. 9 there are signals of the mill 2000 diagnostic system received during the rolling with the proposed algorithm implementation. In this experiment the program setting of screwdown positions of stands No. 7–10 (stand No. 10 was the last rolling one) is done. Besides, the signal of metal presence in the stands is fixed (full lines). In the bottom of the figure, there are oscillograph traces of thickness deviations from the set one, which are received by a signal from output gage. Oscillograms prove that the grow-back along the whole strip is within the tolerance limits. The thickness deviations of the head section are fully compensated. Presented results confirm the efficiency of improved ACSG using the developed strategies of gage control.

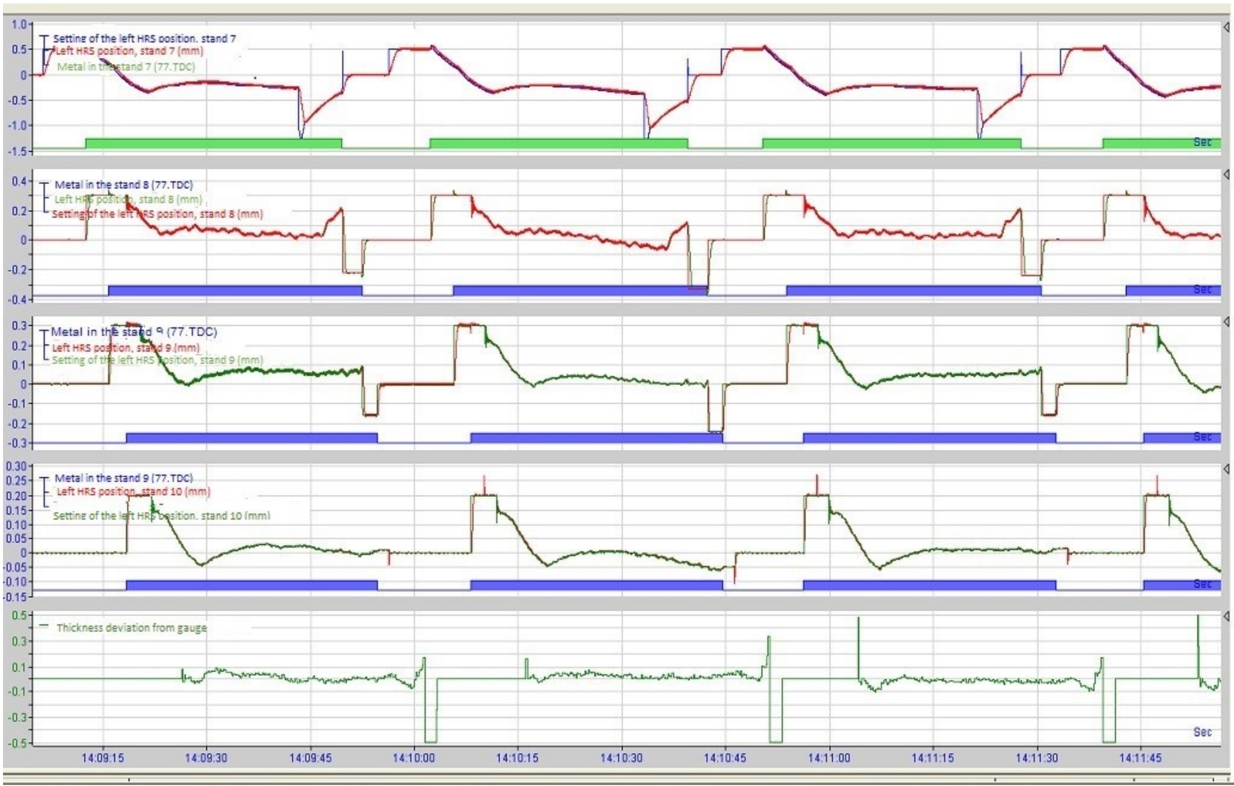


Fig. 9. Oscillograph traces featuring the work of implemented ACSG

5. The development of the electromechanical system of strip tension automatic control

Strategy of tension indirect control with the use of drive (floating) loopers in interstand spaces was implemented in ACST&H of mills 2000 and 2500. The description of ACST&H for mill 2500 is given in [4]. In the place cited, it is proved that it doesn't provide preset parameters of tension control accuracy during rolling the strips of expanded assortment.

The key requirement to ACST&H during thin strips rolling is supporting the specific tensions in range of 0.5–17 N·mm^{-2} in all dynamic modes and herewith, acceptable deviations should not exceed ±10 %, and grow-back should not exceed ±5 % [17].

As it is shown in [18, 19], meeting the increased requirements for dynamic criteria can't be provided only due to computational accuracy increase and process parameters control. The problem aroused how to increase response speed by means of using the resource of thickness control channel implemented on base of hydraulic RS. The most functional is the development of the system of interrelated tension and thickness control, as it is done on cold-rolling mills.

According to theoretic and experimental research, the specific tensions in the interstand spaces of the finishing group of mill 2500 under dynamic mode exceed the steady state value by a factor of 1.5–1.9 %. It leads to the thickness deviation by 5.5–8.7 %. In accordance with specified requirements, this value shouldn't exceed 5 %. Besides, the grow-back caused by tension changes is proved to increase with decreasing of strip thickness. For example, during rolling the strips 4mm thick, the thickness deviations on the initial and final sections are 3.5–4.5 %, and during rolling the strips less than 2 mm thick, it is 11–12.5 %.

The principle of interactive control of the rolling process-dependent parameters in the continuous group of wide-strip mill was set as follows. It is support of the constancy of strip volume per second in interstand spaces under steady-state and dynamic modes is to be provided by simultaneous automatic control of hydraulic screw-down position and the speed of the next stand rolls under control and perturbation actions changing the looper position.

This principle was suggested for implementing together with traditional loop-forming control. The similar principle termed as "Mass control" exists in foreign publications but it concerns the continuous cold-rolling mills [1]. The differences of the study stands group from such type of mills are the presence of loopers and the absence of tension direct gaging sensors in interstand spaces. These features define the fundamental differences of interrelations and, thereafter, the necessary methods and algorithms of control.

To provide technical implementation of the suggested principle, the method of tension and gage interrelated control in the continuous group of HSM [20]. The distinguishing feature is the additional corrective effect on hydraulic RS simultaneously with affecting the speed of the previous stand engine during the looper position change. The functional chart of tension and loop indirect control system implementing the method is given on Fig. 10 [21].

The developed ACST&H consists of fast-active loop of the loop size control with effect on *i*-stand hydraulic RS position, loop control system with effect on speed of i-stand electric driver and "traditional" indirect control system of strip tension in i-space. Additional loop allows to improve tension control accuracy due to roll gap correction during looper position changes. As a result, grow-back decreases along the whole strip. This has positive effects such as quality improvement, reduction of consumption factor connected with decrease of top and bottom scrap, etc.

Mathematic simulation proved that fast-active loop implementation decrease the looper gear lifting time in half (from 0.53 to 0.26 sec) [22]. The preset tension comes into 10 % tolerance zone in 0.13 sec (in 0.57 sec in the existing system), tension over-shoot reduces in 1.7 times (from 37.5 to 22 %), and thickness deviation decreases by factor of 1.4 (from 4.2 to 3 %).

The ACST&H algorithms implemented in controllers of mill 2500 software are studied by experiment. On Fig. 11 there are the strip gage deviation oscillograms received from thickness gauge signals in finishing group output.

The oscillograms on Fig. 11a are obtained during implementing the improved algorithms discussed above in the digital ACST&H. The average thickness deviations are 6.5–7 % and depend on the temperature (evident skid notches). The representative grow-back oscillograms under the implementation of the developed system of tension and thickness interrelated control are given on Fig. 11 b. The grow-back is within the ±4.5 % range. The average thickness is most closely approximate the preset one.

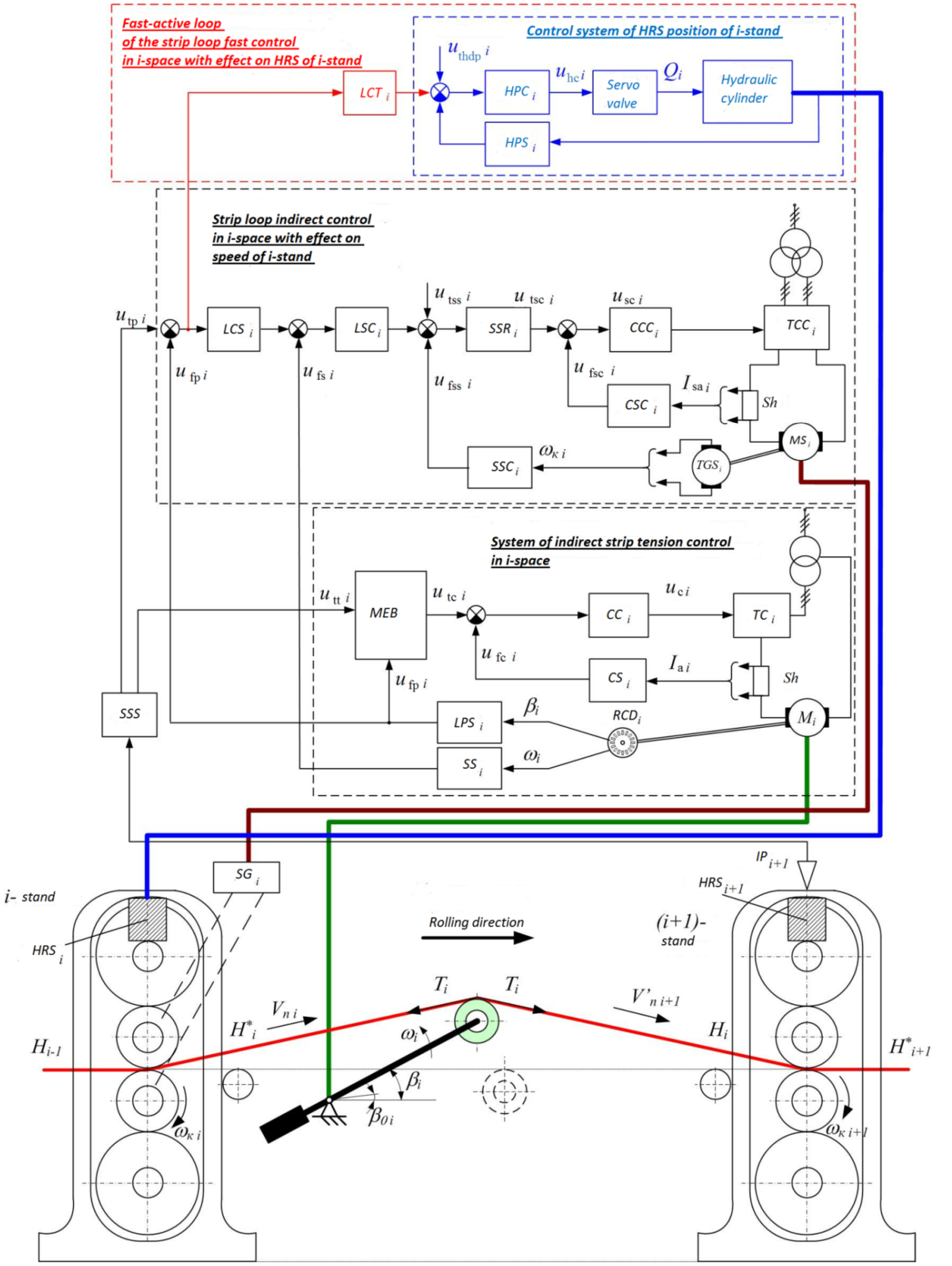
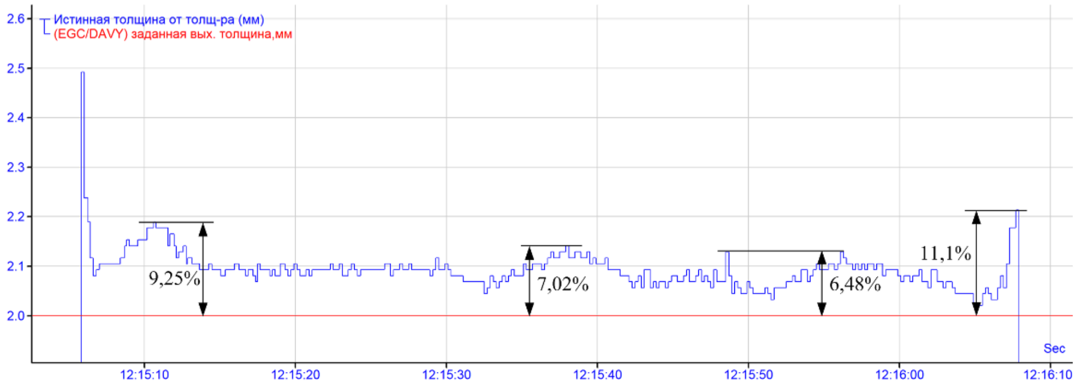
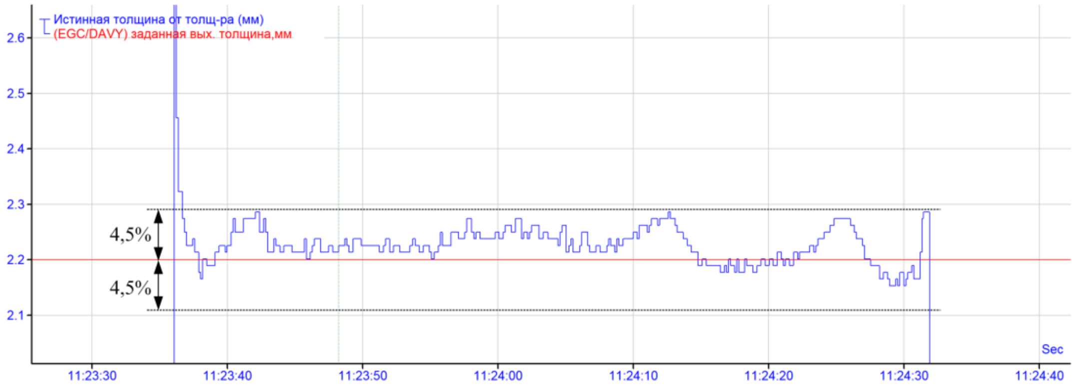


Fig. 10. The functional chart of the developed ACST&H:
TC, TCC, CC, CCC, CS, CSC, SS, SSC, LSC and SSR thyristor converters, current controllers, current sensors, speed sensors, looper speed controllers and stand speed regulators; LPS – looper position sensor; MEB – moment evaluation block; LCS and LCT – looper controllers with effect on stand and with effect on hydraulic roll screwdown; SSS – system signals setter; HPC and HPS – hydraulic screwdown position controller and position sensor; IP – indicator of metal presence in the rollers; M, MS – motors of looper and stand; SG – rolling stand gear



a)



b)

Fig. 11. Oscillograms of strip gage at the mill 2500 output:
a – in the digital ACST&H; b – under the developed improved algorithms implementing

It is proved that additional fast-active tension control channel provides gage deviations within ±5 % tolerance.

Conclusion

Time-testing of the developed technological parameters automatic control systems on mills 2000 and 2500 at Magnitogorsk Iron & Steel Works proved its implementation efficiency.

The following technical effects are provided:

- quality improvement due to grow-back decrease along the strip length;
- reduction of consumption factor by means of improving the thickness control accuracy at the coil ends;
- fault rate reduction due to better conditions of the strip biting.

As it is proved by experiments, the developed systems and algorithms implementation provides the desired dimensional accuracy of extra-thin strip rolling. As a result, technical pre-conditions for hot-strip rolling in broaden assortment are created. Regardless of the assortment, the implement of the developed technical solutions provides cost-effective use of resources due to reductions in scrap and crop ends losses.

Only a part of technical solutions implemented on the above mentioned mills is presented in this article. Moreover, the list of the development is much longer. For example, the developments dealing with a compensation of speed control static error in single-integrating system of electric drive speed automatic control are not presented. It is possible to have a look at them in [23–25]. Besides, the results concerning the development of no-pull automatic control system in the continuous subgroup of roughing mill 2000 group are not presented as well [26–28]. A considerable part of researches is devoted to the dynamic load limiting of roughing group electromechanical systems [29–32]. Besides, the development of the algorithms of plate mill automated process control systems should be mentioned [33, 34]. The investigations in the development of automatic control systems of rolling mills process parameters are in progress. The positive results are reported in periodic scientific publications.

It should be particularly noted that the professionals of Magnitogorsk Iron & Steel Works showed a great interest in the developments, supported them and took part in research, studies and implementation. It is a real positive example of research-industry collaboration which is beneficial to both sides and promotes technical progress in the branch.

References

1. Salganik V.M., Gun I.G., Karandaev A.S., Radionov A.A. *Tonkoslyabovye lineyno-prokatnye agregaty dlya proizvodstva stal'nykh polos* [Thin Slab Foundry-rolling Units for Steel Strips Production]. Moscow, BMSTU Publ., 2003. 506 p.

2. Rode B. [New concepts of economic and flexible manufacturing of high quality hot strips]. *Iron and steel industry of Russia and CIS in XXI century*: Collected papers of International Conference, vol. 3. Moscow, Metallurgy Publ. 1994, pp. 268–273. (in Russ.)

3. Khramshin V.R., Andryushin I.Yu., Shilyaev P.V., Petryakov S.A., Gostev A.N. [Technical Solutions in Automatic Control System of Gage in Hot-roll Mill 2000]. *News of Higher Educational Institutions. Russian Electromechanics*, 2011, no. 4, pp. 41–45. (in Russ.)

4. Shilyaev P.V., Andryushin I.Yu., Golovin V.V., Radionov A.A., Karandaev A.S., Khramshin V.R. [Algorithms of a Digital Automatic System for Tension and Loop Control in a Wide-strip Hot Mill]. *Electrical Engineering*, 2013, no. 10, pp. 3–11. (in Russ.)

5. Shilyaev P.V., Andryushin I.Yu., Golovin V.V., Radionov A.A., Karandaev A.S., Khramshin V.R. Algorithms of a digital automatic system for tension and loop control in a wide-strip hot-rolling mill. *Russian Electrical Engineering*, 2013, no. 84 (10), pp. 533–541.

6. Khramshin V.R., Evdokimov A.S., Kornilov G.P., Radionov A.A., Karandaev A.S. System for Speed Mode Control of the Electric Drives of the Continuous Train of the Hot-Rolling Mill. *Proc. of the 2015 International Siberian Conference on Control and Communications (SIBCON–2015)*. Omsk, Omsk State Technical University Publ., May 21–23, 2015. DOI: 10.1109/SIBCON.2015.7147264

7. Khramshin V.R. [System of Automatic Correction of Stands Electric Drives of Wide-strip Hot Mill]. *Bulletin of the South Ural State University. Ser. Power Engineering*, 2012, iss. 18, no. 37 (296), pp. 60–67. (in Russ.)

8. Karandaev A.S., Khramshin V.R., Andryushin I.Yu., Shubin A.G., Loginov B.M. Improvement of Algorithms for Automatic Gauge Control System of the Hot-Rolling Mill. *Applied Mechanics and Materials*, 2015, vol. 756, pp. 592–597. DOI: 10.4028 /www.scientific.net/AMM.756.592

9. Khramshin V.R., Karandaev A.S., Petryakov S.A., Khramshin R.R. Russian Federation Utility Model Patent 117839, МПК7 B 21 B 37/00. [Strip Gage Automatic Controller for Continuous Wide-strip Hot Mill]. *Official Bulletin "Inventions. Utility Model"*, 2012, no. 19, p. 36. (in Russ.)

10. Khramshin V.R., Karandaev A.S., Petryakov S.A., Galkin V.V., Khramshin R.R. Russian Federation Utility Model Patent 117329, МПК7 B 21 B 37/16. [Corrector for Strip Lead end Gage in Finishing Stand of Wide-strip Hot Mill]. *Official Bulletin "Inventions. Utility Model"*, 2012, no. 18, p. 38. (in Russ.)

11. Karandaev A.S., Khramshin V.R., Andryushin I.Yu., Petryakov S.A., Khramshin R.R. [Correction Technique of Strip Head End Grow-back in Wide-strip Hot Mill Automatic Control System]. *Electrical Engineering*, 2013, no. 8, pp. 34–38. (in Russ.)

12. Karandaev A.S., Khramshin V.R., Andryushin I.Yu., Petryakov S.A., Khramshin R.R. Method for Correction of Gauge Interference of the Head-strip Section in a System for Automated Controlling of the Thickness of a Broad-strip Hot-rolling Mill. *Russian Electrical Engineering,* 2013, 84 (8), pp. 441–445.

13. Galkin V.V., Petryakov S.A., Karandaev A.S., Khramshin V.R. [Automatic Correction of Strip Head End Gage in Hydro-ACSG of Wide-strip Hot Mill]. *News of Higher Educational Institutions. Russian Electromechanics,* 2011, no. 4, pp. 46–50. (in Russ.)

14. Karandaev A.S., Radionov A.A., Khramshin V.R., Andryushin I.Yu., Shubin A.G. Automatic Gauge Control System with Combined Control of the Screw-Down Arrangement Position. *Proc. of the 12th International Conference on Actual Problems of Electronic Instrument Engineering (APEIE-2014)*, Novosibirsk, 2014, vol. 1, pp. 88–94. DOI: 10.1109/APEIE.2014.7040794

15. Karandaev A.S., Khramshin V.R. [Analysis of Strip Gage Automatic Correction System on Wide-strip Hot Mill]. *News of Higher Educational Institutions. Russian Electromechanics*, 2013, no. 4, pp. 39–46. (in Russ.)

16. Khramshin V.R., Karandaev A.S., Radionov A.A., Khramshin R.R. Study of Thickness Control of Strip Head Section Using Mathematical Simulation Methods. *Bulletin of the South Ural State University. Series "Power Engineering"*, 2013, iss. 13, no. 1, pp. 144–153.

17. Karandaev A.S., Evdokimov S.A., Chertousov A.A., Khramshin V.R. [Tension and Loop Automatic Control Cross-coupled System for Wide-strip Hot Mill]. *News of Higher Educational Institutions. Russian Electromechanics*, 2004, no. 2, pp. 21–27. (in Russ.)

18. Khramshin V.R. *Razrabotka electrotekhnicheskikh system nepreryvnoy gruppy stana goryachey prokatki pri rashirenii sortamenta polos: dis. d-ra tekhn. nauk* [Electrical Systems Development for Hot-roll Mill Continuous Train under Strips Assortment Expansion: Doctorate Thesis]. Magnitogorsk, NMSTU Publ., 2013. 360 p.

19. Selivanov I.A., Karandaev A.S., Evdokimov S.A., Khramshin V.R., Shemetova A.A., Lukin A.A. [Automatic Electric Drives Updating and Power Equipment Diagnostics]. *News of Higher Educational Institutions. Russian Electromechanics*, 2009, no. 1, pp. 5–11. (in Russ.)

20. Karandaev A.S., Khramshin V.R., Shilyaev P.V., Andryushin I.Yu., Golovin V.V., Ponomarev P.L. [Russian Federation Patent of Invention 2446026, МПК7 B 21 B 37/48. Method of Strip Tension Automatic Control in Interstand Space of Wide-strip Hot Mill]. *Official Bulletin "Inventions. Utility model"*, 2012. no. 9, p. 117. (in Russ.)

21. Khramshin V.R. [Development and Implementation of Automated Electric Drives and Control Systems of Technological Parameters of Hot Rolling Broad-strip Mill]. *Bulletin of Ivanovo State Power University*, ISPU Publ., 2012, no. 6, pp. 100–104. (in Russ.)

22. Karandaev A.S., Khramshin V.R., Andryushin I.Yu., Golovin V.V., Shilyaev P.V., Petryakov S.A., Lukin A.A. [New Technical Solutions in Electric Drives and in Control Systems of Hot Rolling Mills Process Parameters]. *News of Tula State University. Technical sciences*, TSU Publ., 2010, iss. 3, part. 2, pp. 34–40. (in Russ.)

23. Andryushin I.Yu., Galkin V.V., Golovin V.V., Shilyaev P.V., Karandaev A.S., Khramshin V.R., Khramshin R.R. [Russian Federation patent of invention 2477187, МПК7 B 21 B 37/52. Method of Rolling Process Automatic Control in Continuous Train]. *Official Bulletin "Inventions. Utility Model"*, 2013, no. 7, p. 75. (in Russ.)

24. Khramshin V.R. [Methods of static compensation of stands electric drives speed deviations on wide-strip hot mill]. *Electrical Engineering*, 2013, no. 4, pp. 49–55. (in Russ.)

25. Karandaev A.S. [Improvement of Rolling Units Automatic Electric Drives]. *Russian Internet Journal of Industrial Engineering*, 2014, no. 1, pp. 3–15. (in Russ.)

26. Andryushin I.Yu., Galkin V.V., Golovin V.V., Karandaev A.S., Radionov A.A., Khramshin V.R. [Automatic Correction of Mill 2000 Stands Electric Drives Speed During Hollow Billet Rolling]. *News of Higher Educational Institutions. Russian Electromechanics*, 2011, no. 4, pp. 31–35. (in Russ.)

27. Karandaev A.S., Khramshin V.R., Galkin V.V., Gostev A.N. [Development of Speed Match Algorithm of Roughing Hot-roll Mill Group Electric Drives]. *Bulletin of the South Ural State University. Ser. Power Engineering*, 2011, iss. 16, no. 34 (251), pp. 35–41. (in Russ.)

28. Karandaev A.S., Khramshin V.R., Radionov A.A., Andryushin I.Yu., Galkin V.V., Gostev A.N. [Speed Modes Matching for Continuous Mill Train Electric Drives]. *Bulletin of Ivanovo State Power University*, ISPU Publ., 2013, no. 1, pp. 98–103. (in Russ.)

29. Andryushin I.Yu., Galkin V.V., Gostev A.N., Kazakov I.V., Evdokimov S.A., Karandaev A.S., Khramshin V.R., Khramshin R.R. [Russian Federation Patent of Invention № 2494828, MPK B21B37/52. Method of Strip Tension Automatic Control in Continuous Mill Roughing Train]. *Official Bulletin "Inventions. Utility Model"*, 2013, no. 28, p. 31. (in Russ.)

30. Khramshin V.R., Karandaev A.S., Evdokimov S.A., Andryushin I.Yu., Shubin A.G., Gostev A.N. [Reduction of the Dynamic Loads in the Universal Stands of a Rolling Mill]. *Metallurgist*, 2015, no. 4, pp. 41–47. (in Russ.)

31. Khramshin V.R., Karandaev A.S., Evdokimov S.A., Andryushin I.Yu., Shubin A.G., Gostev A.N. Reduction of the Dynamic Loads in the Universal Stands of a Rolling Mill. *Metallurgist*, 2015, vol. 59, № 3–4, pp. 315–323. DOI: 10.1007/s11015-015-0103-8

32. Khramshin V.R., Karandaev A.S., Radionov A.A., Andryushin I.Yu., Gostev A.N. [Reduction of Dynamic Loads of Hot-roll Mill Roughing Trains Mechanic and Electric Equipment. *Russian Internet Journal of Industrial Engineering*, 2013, no. 2, pp. 69–77. (in Russ.)

33. Baskov S.N., Karandaev A.S., Osipov O.I. [Power Parameters of Drives and the Mill 2800 Profiled Slabbing System]. *Drive Technology*, 1999, no. 1–2, pp. 21–24. (in Russ.)

34. Shilyaev P.V., Usatiy D.U., Radionov A.A. [Plate Rolling Automation on Mill 5000]. *News of Higher Educational Institutions. Russian Electromechanics*, 2011, no. 4, pp. 15–18. (in Russ.)

Received 5 December 2015

УДК 621.771.016 **DOI: 10.14529/ctcr160111**

СОВЕРШЕНСТВОВАНИЕ СИСТЕМ АВТОМАТИЧЕСКОГО РЕГУЛИРОВАНИЯ ТЕХНОЛОГИЧЕСКИХ ПАРАМЕТРОВ ШИРОКОПОЛОСНОГО СТАНА ГОРЯЧЕЙ ПРОКАТКИ

С.С. Воронин, В.Р. Гасияров, Е.А. Маклакова, А.А. Радионов
Южно-Уральский государственный университет, г. Челябинск

Отмечено, что современной тенденцией развития прокатного производства является расширение сортамента широкополосных станов горячей прокатки за счет производства особо тонкой горячекатаной полосы взамен холоднокатаной. На примере широкополосных станов 2000 и 2500 ОАО «Магнитогорский металлургический комбинат» обоснована целесообразность совершенствования основных систем автоматического регулирования технологических параметров (натяжения, толщины, скорости прокатки). Рассмотрены алгоритмы управления скоростными режимами электроприводов, обеспечивающие автоматическое пропорциональное регулирование скоростей валков клетей чистовой группы при управляющих и возмущающих воздействиях с передачей корректирующего воздействия против хода прокатки. Представлены уточненные цифровые алгоритмы регулирования натяжения в динамических режимах, обеспечивающие снижение продольной разнотолщинности полосы за счет повышения точности вычислений момента электропривода петледержателя и размера петли в межклетевом промежутке. Рассмотрена структура усовершенствованной системы автоматического регулирования толщины полосы (САРТ). Система реализует способ регулирования, основанный на сочетании косвенного регулирования с усреднением показаний датчиков за заданный промежуток времени, прямого регулирования по сигналу от выходного толщиномера и внешней коррекции, обеспечивающей компенсацию возмущающих воздействий и перераспределение обжатий по клетям чистовой группы. Представлена разработанная система автоматической коррекции толщины головного участка путем разведения валков перед входом полосы в клеть с последующим их возвращением в заданную позицию для прокатки основного участка полосы. Представлены результаты экспериментальных исследований усовершенствованной САРТ на действующем прокатном стане. Обоснованы и рассмотрены способ и система взаимосвязанного регулирования натяжения и толщины полосы, согласно которым осуществляется автоматическая коррекция положения гидравлического нажимного устройства предыдущей клети при управляющих и возмущающих воздействиях, вызванных изменением положений петледержателя либо нажимного устройства последующей клети. Отмечены результаты исследований и промышленного внедрения разработанных систем, подтвердившие технико-экономическую эффективность, обеспечиваемую за счет снижения материалоемкости, повышения качества продукции и устойчивости технологического процесса.

Ключевые слова: широкополосный стан горячей прокатки, непрерывная группа клетей, технологические параметры, системы автоматического регулирования, совершенствование, технические решения, экспериментальные исследования, внедрение.

Литература

1. *Тонкослябовые литейно-прокатные агрегаты для производства стальных полос / В.М. Салганик, И.Г. Гун, А.С. Карандаев, А.А. Радионов. – М.: МГТУ им. Н.Э. Баумана, 2003. – 506 с.*
2. *Роде, В. Новые концепции экономического и гибкого производства высококачественных горячих штрипсов / В. Роде // Черная металлургия России и стран СНГ в XXI веке: сб. тр. междунар. конф. – М.: Металлургия, 1994. – Т. 3. – С. 268–273.*
3. *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.*
4. *Алгоритмы цифровой системы автоматического регулирования натяжения и петли широкополосного стана горячей прокатки / П.В. Шиляев, И.Ю. Андрюшин, В.В. Головин и др. // Электротехника. – 2013. – № 10. – С. 3–11.*
5. *Algorithms of a digital automatic system for tension and loop control in a wide-strip hot-rolling mill / P.V. Shilyaev, I.Yu. Andryushin, V.V. Golovin et al. // Russian Electrical Engineering. – 2013. – No. 84 (10). – P. 533–541.*
6. *System for Speed Mode Control of the Electric Drives of the Continuous Train of the Hot-Rolling Mill / V.R. Khramshin, A.S. Evdokimov, G.P. Kornilov et al. // Proceedings of the 2015 International Siberian Conference on Control and Communications (SIBCON–2015). Omsk: May 21–23, 2015. – Omsk: Omsk State Technical University, 2015. DOI: 10.1109/SIBCON.2015.7147264.*
7. *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.*
8. *Improvement of Algorithms for Automatic Gauge Control System of the Hot-Rolling Mill / A.S. Karandaev, V.R. Khramshin, I.Y. Andryushinet al. // Applied Mechanics and Materials. – 2015. – Vol. 756. – P. 592–597. DOI: 10.4028 /www.scientific.net/AMM.756.592.*
9. *Патент РФ на полезную модель 117839, МПК7 В 21 В 37/00. Устройство автоматического регулирования толщины полосы непрерывного широкополосного стана горячей прокатки / В.Р. Храмшин, А.С. Карандаев, С.А. Петряков, Р.Р. Храмшин // БИПМ. – 2012. – № 19. – С. 36.*
10. *Патент РФ на полезную модель 117329, МПК7 В 21 В 37/16. 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 // БИПМ. – 2012. – № 18. – С. 38.*
11. *Способ коррекции разнотолщинности головного участка полосы в системе автоматического регулирования толщины широкополосного стана горячей прокатки / А.С. Карандаев, В.Р. Храмшин, И.Ю. Андрюшин и др. // Электротехника. – 2013. – № 8. – С. 34–38.*
12. *Method for correction of gauge interference of the head-strip section in a system for automated controlling of the thickness of a broad-strip hot-rolling mill / A.S. Karandaev, V.R. Khramshin, I.Yu. Andryushin et al. // Russian Electrical Engineering. – 2013. – 84 (8). – P. 441–445.*
13. *Автоматическая коррекция толщины головного участка полосы в гидро-САРТ 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. *Automatic Gauge Control System with Combined Control of the Screw-Down Arrangement Position / A.S. Karandaev, A.A. Radionov, V.R. Khramshin et al. // Proceedings of the 12th International Conference on Actual Problems of Electronic Instrument Engineering (APEIE-2014). – Novosibirsk, 2014. – Vol. 1. – P. 88–94. DOI: 10.1109/APEIE.2014.7040794.*
15. *Карандаев, А.С. Исследование системы автоматической коррекции толщины полосы на широкополосном стане горячей прокатки / А.С. Карандаев, В.Р. Храмшин // Известия вузов. Электромеханика. – 2013. – № 4. – С. 39–46.*
16. *Study of Thickness Control of Strip Head Section Using Mathematical Simulation Methods / V.R. Khramshin, A.S. Karandaev, A.A. Radionov, R.R. Khramshin // Вестник ЮУрГУ. Серия «Энергетика». – 2013. – Вып. 13. – № 1. – С. 144–153.*
17. *Система автоматического регулирования натяжения и петли с перекрестными связями для широкополосного стана горячей прокатки / А.С. Карандаев, С.А. Евдокимов, А.А. Чертоусов, В.Р. Храмшин // Известия вузов. Электромеханика. – 2004. – № 2. – С. 21–27.*

18. Храмшин, В.Р. Разработка электротехнических систем непрерывной группы стана горячей прокатки при расширении сортамента полос: дис. ... д-ра техн. наук / В.Р. Храмшин. – Магнитогорск: МГТУ, 2013. – 360 с.

19. Совершенствование автоматизированных электроприводов и диагностика силового электрооборудования / И.А. Селиванов, А.С. Карандаев, С.А. Евдокимов и др. // Известия вузов. Электромеханика. – 2009. – № 1. – С. 5–11.

20. Патент РФ на изобретение 2446026, МПК7 B 21 B 37/48. Способ автоматического регулирования натяжения полосы в межклетевом промежутке широкополосного стана горячей прокатки / А.С. Карандаев, В.Р. Храмшин, П.В. Шиляев, И.Ю. Андрюшин, В.В. Головин, П.Л. Пономарев // БИПМ. – 2012. – № 9. – С. 117.

21. Храмшин, В.Р. Разработка и внедрение автоматизированных электроприводов и систем регулирования технологических параметров широкополосного стана горячей прокатки / В.Р. Храмшин // Вестник Ивановского государственного энергетического университета. – 2012. – № 6. – С. 100–104.

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

23. Патент РФ на изобретение 2477187, МПК7 B 21 B 37/52. Способ автоматического управления процессом прокатки в непрерывной группе клетей / И.Ю. Андрюшин, В.В. Галкин, В.В. Головин, П.В. Шиляев, А.С. Карандаев, В.Р. Храмшин, Р.Р. Храмшин // БИПМ. – 2013. – № 7. – С. 75.

24. Храмшин, В.Р. Способы компенсации статических отклонений скорости электроприводов клетей широкополосного стана горячей прокатки / В.Р. Храмшин // Электротехника. – 2013. – № 4. – С. 49–55.

25. Карандаев, А.С. Совершенствование автоматизированных электроприводов агрегатов прокатного производства / А.С. Карандаев // Машиностроение: сетевой электронный научный журнал. –2014. – №1. – С. 3–15.

26. Автоматическая коррекция скоростей электроприводов клетей стана 2000 при прокатке трубной заготовки / И.Ю. Андрюшин, В.В. Галкин, В.В. Головин и др. // Известия вузов. Электромеханика. – 2011. – № 4. – С. 31–35.

27. Совершенствование алгоритма согласования скоростей электроприводов клетей черновой группы стана горячей прокатки / А.С. Карандаев, В.Р. Храмшин, В.В. Галкин, А.Н. Гостев // Вестник ЮУрГУ. Серия «Энергетика». – 2011. – Вып. 16. – № 34 (251). – С. 35–41.

28. Согласование скоростных режимов электроприводов клетей непрерывной группы прокатного стана / А.С. Карандаев, В.Р. Храмшин, А.А. Радионов и др. // Вестник Иванов. гос. энерген. ун-та. – 2013. – № 1. – С. 98–103.

29. Патент РФ на изобретение №2494828, МПК B21B37/52. Способ автоматического регулирования натяжения полосы в черновой группе клетей непрерывного прокатного стана / И.Ю. Андрюшин, В.В. Галкин, А.Н. Гостев, И.В. Казаков, С.А. Евдокимов, А.С. Карандаев, В.Р. Храмшин, Р.Р. Храмшин // БИПМ – 2013. №28. – С. 31.

30. Снижение динамических нагрузок в универсальных клетях прокатного стана / В.Р. Храмшин, А.С. Карандаев, С.А. Евдокимов и др. // Металлург. – 2015.– № 4. – С. 41–47.

31. Reduction of the Dynamic Loads in the Universal Stands of a Rolling Mill / V.R. Khramshin, A.S. Karandaev, S.A. Evdokimov et al. // Metallurgist. – 2015. – Vol. 59. № 3–4, July. – P. 315–323. DOI: 10.1007/s11015-015-0103-8.

32. Снижение динамических нагрузок механического и электрического оборудования черновой подгруппы клетей стана горячей прокатки / В.Р. Храмшин, А.С. Карандаев, А.А. Радионов и др. // Машиностроение: сетевой электронный научный журнал. – 2013. – №2. – С. 69–77.

33. Басков, С.Н. Энергосиловые параметры приводов и система профилированной прокатки слябов стана 2800 / С.Н. Басков, А.С. Карандаев, О.И. Осипов // Приводная техника. – 1999. – № 1–2. – С. 21–24.

34. Шиляев, П.В. Автоматизация процесса прокатки толстого листа на стане 5000 / П.В. Шиляев , Д.Ю. Усатый, А.А. Радионов // Известия вузов. Электромеханика. – 2011. – № 4. – С. 15–18.

Воронин Станислав Сергеевич, младший научный сотрудник базовой кафедры «Мехатроника», Южно-Уральский государственный университет, г. Челябинск; voronsot@mail.ru.

Гасияров Вадим Ришитович, канд. техн. наук, доцент, заведующий базовой кафедрой «Мехатроника»; Южно-Уральский государственный университет, г. Челябинск; gasiiarovvr@susu.ac.ru.

Маклакова Екатерина Андреевна, аспирант базовой кафедры «Мехатроника», Южно-Уральский государственный университет, г. Челябинск; karyakina-katya@yandex.ru.

Радионов Андрей Александрович, д-р техн. наук, профессор базовой кафедры «Мехатроника», Южно-Уральский государственный университет, г. Челябинск; radionovaa@rambler.ru.

Поступила в редакцию 5 декабря 2015 г.

ОБРАЗЕЦ ЦИТИРОВАНИЯ

Development of automatic control system of hot-strip mill process parameters / S.S. Voronin, V.R. Gasiyarov, E.A. Maklakova, A.A. Radionov // Вестник ЮУрГУ. Серия «Компьютерные технологии, управление, радиоэлектроника». – 2016. – Т. 16, № 1. – С. 121–136. DOI: 10.14529/ctcr160111

FOR CITATION

Voronin S.S., Gasiyarov V.R., Maklakova E.A., Radionov A.A. Development of Automatic Control System of Hot-Strip Mill Process Parameters. *Bulletin of the South Ural State University. Ser. Computer Technologies, Automatic Control, Radio Electronics*, 2015, vol. 16, no. 1, pp. 121–136. DOI: 10.14529/ctcr160111