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## MINIMIZATION OF DYNAMIC CHANGES IN THE TENSION OF LONG PRODUCTS BEHIND THE OUTLET CAGE IN ROLLING STOCK PRODUCTION IN COILS

**Purpose.** Justification of technical solutions as to the reduction of the amplitude and reduction of the dynamic change duration in the tension of the rolling stock at the exit of the output cage when moving to winding a new layer to an acceptable level in terms of its effect on the resulting profile of the rolled product through the control of the rotation frequency of an output cage.

**Methodology.** The conducted research was based on a complex model of the process of rolled steel winding with a Garrett-type winder and the tension of rolled steel in the area of the exit cage-winder. To control the actual amount of tension at the output cage exit, it is suggested to use the amount of free deflection of the rolled steel directly behind the cage. The research was carried out by simulating the process of rolled steel winding according to the basic control scheme and control schemes that predict the influence on both drives, i.e. the winder drive and the output cage drive according to the actual value of tension, in various combinations with further analysis and comparison of the obtained results.

**Findings.** It was established that the correction for the deviation of the actual rolling tension in the finishing cage-winder area from the specified value of the winding current of the winder electric drive does not eliminate rolling tension when switching to the next layer winding and the oscillating form of the transition process, which are characteristic of the basic rolling winding scheme. In turn, the correction of the rotation frequency of the output cage rolls drive reduces the amplitude of the roll tension jerk by almost half with a simultaneous reduction in the time of the transition process and readjustment when switching to a new layer winding.

**Originality.** It has been shown for the first time that the introduction of the roll tension control circuit by correcting the high-speed rolling mode of the output cage ensures minimization of dynamic changes in the rolled steel tension when switching to a new layer winding and reduces the probability of local tightening of rolled steel profile.

**Practical value.** The use of the described technical solutions in the control system of the section of rolled products winding of the small-grade wire mill DSDS 250/150-6 PJSC “ArcelorMittal Kryvyi Rih” ensures the improvement of the commercial properties of the winding of rolled products produced on the rolling mill.

**Keywords:** *winder, rolling tension, control of the winding current, control of the rolling speed mode*

**Introduction.** The production of graded rolled products in coils is a promising world-wide direction for the rolled products development due to the significant reduction of metal losses when used in machine building, hardware industry and construction in comparison with the use of the same rolled products supplied in rods.

Today's world production of medium and large coils is mainly focused on special steels for the automotive industry, as well as for cold stamping and/or forging and drawing.

Therefore, modern lines for the production of rolled products in coils must meet the following basic requirements:

- 1) high output productivity;
- 2) defect-free rolled surface in coils;
- 3) homogeneous technological characteristics of rolled products in coils;
- 4) the compactness of the coils and the uniform distribution of rolls facilitating storage, transportation as well as safe and easy unwinding.

The absence of contraction and other defects on the rolled surface is a fundamental requirement for the production lines of graded rolled products. This problem is almost completely solved on rolling mills equipped with Stelmor lines with free forming of rolls, for the range of cross-section sizes of rolled products supposed to be produced by this line in contrast to the production of graded rolled products coils of medium and large cross-sections obtained by winding on the Garrett-type winders.

The peculiarity of coiling of rolled products on Garrett-type winders is that the winding is carried out with the tension of the rolled products before the coiler. Traditionally, tension value is set by the “winding current”, which is determined at the current regulator of the winder's electric drive control system input and corresponds to the required value of tension of the rolled material before the winder. Since the output cage is connected to the winder through a roll, the roll tension before the winder and that directly behind the output cage are closely related.

The rolling process is accompanied by phenomena that lead to a dynamic change in the tension of the rolled material both before the winder and behind the output cage. Such dynamic changes in tension are caused by two main factors. First of all, there is a surge in the linear speed of the rolled product at the point of its adhesion to the coil at the beginning of a new layer winding and secondly, a change in the length of the rolled product between the winder and the cage with the stacker movement.

Fluctuations in rolled product tension negatively influence the quality indicators of commercial products. Thus, the dynamic drop in tension leads to local reductions in the density of rolled coils in a winding, which negatively affects the density of the winding itself and the process of unwinding at the rolled product consumer end. Excessive tension can lead to local tightening of the profile, that is, failure to fulfill the third point of the requirements that were given above.

Thus, the reduction of dynamic changes in tension when winding graded rolled products on Garrett-type winders is an urgent problem.

**Literature review.** For the past two decades, the Danieli Group company has been the leader in the production of rolled coil production lines, which has built more than sixty enterprises of this type around the world for the given period of time [1, 2]. Control systems and the technical solutions used ensure temperature stabilization at the exit from the finishing group of cages, minimization of damage to the rolled surface, regulation of the winding density of coils, uniformity of the technological characteristics of the rolled products throughout the entire coil, uniform distribution of turns in the coil, adjustable cooling of the rolled products. However, in the literature the results of the operation of control systems in the form of advertising are given as research, without indicating the principle of operation and description of the used technical solutions thanks to which positive results are obtained [3, 4].

The analysis of works [5, 6] shows that the two main problems in the production of rolled products in coils are the deformation of its surface and the change in geometric dimensions along the length of the rolled product during the winding process. To solve the first problem the transport lines are equipped with support rollers with air/oil lubrication [1, 3], but the description of additional devices for creating tension before the winder, e.g. trib apparatus is not considered.

It should be noted that the effort of transporting/braking the rolled product in the trib apparatus is created due to the deformation of the rolled product surface which, in the context of requirements for the quality of the rolled product is undesirable.

The solution to the second problem is possible due to the improvement of the winding process [7] and regulation of the tension of the rolled steel between the output cage and the winder [5]. If the first problem is of a technological nature and requires making significant changes to the existing equipment [3, 7], the second one can be solved by implementing a modern roll tension control system [5], which does not require significant material costs.

As it is known, the control system must ensure the regulation of the winding density of the coils and the rolled product's technological characteristics homogeneity throughout the coil and the uniform distribution of turns in the coil [4, 5], which is difficult to ensure without minimizing the amplitude of dynamic tension changes during the process of rolled product winding.

Thus, the task of developing technical solutions for managing rolled products tension to ensure the minimization of its dynamic changes under the influence of technological disturbances and to prevent local contraction of rolled products profile while winding is urgent.

Proceeding from the peculiarities of the technological process of rolling, it is impossible to conduct a large number of studies with changes in its parameters, as this can lead to the occurrence of abnormal or emergency situations, spoilage of products and, as a consequence, material losses [3, 5]. In addition, not all technological parameters can be measured [8]. Therefore, the main studies on rolling processes and the synthesis of control systems are performed using analytical and simulation models [9, 10].

It should be noted that an approach based on static models cannot be used to solve the problem of reducing the tension fluctuations of the rolling stock in the section of the outlet cage – Garrett-type winder, which, for example, was used by Hnatushenko and Zheldak in the publication of 2021 to solve the problem of optimizing metal consumption in the production of small-grade rolled products as the rolling process is dynamic with virtually no fixed parameters. The analytical technological model of rolled steel coiling [5] developed by the authors, revealed the presence of various types of nonlinear links in the model, many of which are described by differential equations, and a large number of interconnected contours with intersecting connections that do not allow analytically solving the problem of synthesizing the control system of

rolled steel winding which would ensure the reduction of dynamic changes in tension in the area of the outlet cage-winder.

Thus, solving the problem of reducing dynamic changes in tension when winding graded rolled products on Garrett-type winders is an urgent problem that requires a non-standard approach.

**Purpose.** The purpose of the article is the development and research of scientific and technical solutions that ensure the reduction of the amplitudes of the dynamic change in the tension of rolled steel in the area of the output cage – the winder when the process of winding is affected by technological disturbances, specific for the process of winding rolled steel with a Garrett type winder.

**Methods.** The research was carried out based on the technological model of the rolling process winding with Garrett-type winders, which covers the area of the output cage-winder, previously developed by the authors [5]. At the first stage, on the basis of the theory of rolling and the resistance of materials, requirements were formulated for the limit values of the tension values, at which the minimum permissible density of the rolled product adhering to the body of the coil (the lower limit of the tension of the rolled product) and the maximum limit value of the tension (the upper limit of the tension of the rolled product), at which there is no “noticeable” contraction of the rolling stock profile. At the second stage possible options for correcting the rolling stock tension in the area output cage-winder were analyzed by controlling the winding process through correcting the winding current of the winder and correcting the rotation frequency of the discharge cage rolls. The location and method of rolling tension control are substantiated which ensure the implementation of the research results. At the next stage the rolling process was modeled according to the previously accepted scheme, separately and together with the winding current correction contours and the output cage rotation frequency correction. At the fourth stage the simulation results were analyzed and conclusions were formulated.

**Results.** In order to estimate the minimum tension of the rolled product, which ensures tight pressing of the rolled product to the body of the coil, the bending process of the rolled product at the point of its first contact with the coil is analyzed from the standpoint of the theory of material resistance, and the expression is obtained

$$\sigma_{p\_m\_min} = \sigma_{t\_p} \cdot \frac{4 \cdot D_p}{3 \cdot \pi \cdot D_{n\_m}} + \rho_p \cdot V_p^2,$$

where  $\sigma_{p\_m\_min}$  is the minimum allowable specific tension in the rolling stock during winding;  $\sigma_{t\_p}$  is the yield point of rolled steel;  $D_p$  is a rolled diameter;  $D_{n\_m}$  is the diameter of the rolling stock on the winder;  $\rho_p$  is density of rolled material (steel);  $V_p$  is the linear rolling speed.

Thus, in order to always ensure tight pressing of the rolled product to the body of the coil, it is necessary to maintain the specific tension in the rolled product before the winder  $\sigma_{p\_m}$ , more than  $\sigma_{p\_m\_min}$

$$\sigma_{p\_m} > \sigma_{p\_m\_min}.$$

To estimate the order of the specific tension in the rolling stock, as initial data is taken the following:  $D_p = 16$  mm,  $D_{n\_m} = 1000$  mm,  $V_p = 15$  m/s,  $\sigma_{t\_p} = 100$  N/mm<sup>2</sup> (the yield strength of low-carbon low-alloy steel for a temperature of 800 °C). With the given values, the minimum specific tension in the rolled product required for its plastic bending is approximately 0.85 N/mm<sup>2</sup>, and the minimum allowable specific tension of the rolled product before winding is – 2.6 N/mm<sup>2</sup>. In general, the lower limit of the specific tension can be estimated as 3–5 N/mm<sup>2</sup> for the Garrett winders used for winding graded rolled products at the DSDS 250/150-6 fine grade wire mill of PJSC “ArcelorMittal Kryvyi Rih”.

The maximum allowable rolling tension is estimated based on the handbook on the theory of rolling, edited by V. I. Zyuz-

ina and A.V.Tretyakov. According to the handbook, three main zones have been identified which characterize the influence of tension on the geometric dimensions of rolled products at the exit from the cage.

The first zone is the zone of practically elastic deformations of rolled steel, which occurs when

$$\sigma_p \leq \sigma_{up},$$

where  $\sigma_p$  is the specific stress of the rolling stock;  $\sigma_{up}$  is the conditional elastic limit (for low-carbon, low-alloy steel at a rolling temperature of 850–1100 °C, it is 10–15 N/mm<sup>2</sup>).

The second zone namely the zone of elastic-plastic deformations of rolled steel occurs when

$$\sigma_{up} < \sigma_p \leq \sigma_{pl},$$

where  $\sigma_{pl}$  is the conditional yield strength (for low-carbon, low-alloy steel at a rolling temperature of 850–1100 °C, it is 25–50 N/mm<sup>2</sup>).

The third zone – the zone of plastic deformation of the rolled product takes place when

$$\sigma_p > \sigma_{pl}.$$

To ensure stable cross-sectional dimensions of the rolled product, its winding must be carried out in the first zone of its tension – the zone of elastic deformations.

The static value of the rolled product tension is determined by the given winding current, which is set in accordance with the technological instructions for the current profile size of the rolled product, its temperature before the coiling, steel grade and other factors. However, in order to manage the rolling tension, it is necessary to have information about its current actual value. Most of the methods used in world practice are based either on measuring the force effect of the rolling stock on a special roller in contact with the rolling stock, or on evaluating the load change (static moment, armature current) of the cage motor with which the rolling stock is in contact.

The first group of methods involves putting a special roller in contact with the rolled product on the rolling line, which is undesirable from the point of view of the reliability of the operation of this device at high rolling speeds and adding a source of damage to the surface of the rolled product. The second group of methods proved its low effectiveness in controlling the tension of rolled products with a relatively small cross-sectional area of the rolled products, i.e. the component of the moment from the tension is significantly smaller than the component associated with the deformation of the rolled products in the cage.

The method developed by domestic scientists Kukushkin, Grinberg, Chygrynskyi and Karpinsky was the most suitable from the perspective of operational properties and accuracy of rolling tension control, which is successfully used to control the tension of rolled products between cages on the fine grade wire mill DSDS 250/150-6 of PJSC “ArcelorMittal Kryvyi Rih”.

According to this method, the deflection of the rolled sheet is controlled by a photoelectric sensor, and the tension is calculated according to the formula

$$\sigma_{p\_kl} = \sigma_{kr} \cdot \left( \frac{h_{pr0}}{h_{pr}} - 1 \right),$$

where  $\sigma_{p\_kl}$  is the specific tension of the rolling stock for the output cage;  $\sigma_{kr}$  is critical specific voltage;  $h_{pr0}$  is the height of the boom of the roll deflection at zero tension;  $h_{pr}$  is the height of the boom of the roll deflection.

For the last two parameters, we have

$$h_{pr0} = \frac{5}{384} \cdot \frac{\rho_s \cdot g \cdot l_{pr0}^4}{E_{u\_kl} \cdot r_{i\_p}^2}; \quad \sigma_{kr} = \frac{\pi^2 \cdot E_{u\_kl} \cdot r_{i\_p}^2}{l_{pr0}^2},$$

where  $\rho_s$  is the density of steel;  $E_{u\_kl}$  is the weighted average value of the modulus of elasticity (Young's modulus);  $l_{pr0}$  is

the length of the section of the roll forming deflection;  $r_{i\_p}$  is the radius of inertia of the rolled cross section in the vertical plane.

It is obvious that it is possible to increase the dynamic accuracy of the stabilization of the roll tension in the section of the winder-cage by introducing feedback on the tension of the rolled sheet in this section.

Since the most critical factor for the quality of the rolling stock is its tension just behind the output cage, it is advisable to organize a counterpoint right there. All the more so because sensors which monitor the temperature and availability of rolled products are placed behind the output cage and there is enough space for organizing the bending of the rolled products.

You can set the value of the tension of the rolling stock by the output cage –  $\sigma_{p\_kl\_z}$ , by setting the value of the deflection  $h_{pr\_z}$ . Then for the voltage feedback comparison node we have

$$\sigma_{p\_kl\_z} - \sigma_{p\_kl} = \sigma_{kr} \cdot h_{pr0} \cdot \frac{h_{pr} - h_{pr\_z}}{h_{pr} \cdot h_{pr\_z}}.$$

Therefore, the comparison node can be implemented in the form presented in Fig. 1, where  $\sigma_{p\_z}$  – is the given specific tension of the rolled steel.

Based on the results of the analysis of the analytical technological model of coil winding given in [5], it was concluded that there are only two channels for influencing the tension of the coil between the output cage and the winder. This is the correction of the task of the current of the winder drive and/or the correction of the task of the rotation frequency of the electric drive of the exhaust cage.

The structure of the complex model of the outlet cage-winder area with the contours of the tension correction of the rolling stock behind the outlet cage is shown in Fig. 2. The block for calculating the variable parameters of coiling rolled products is disclosed in [5].

Fig. 2 shows:  $\omega_{dv\_kl\_z}$  – engine rotation speed of the exhaust cage which is set;  $\omega_{kl}$  – speed of rotation of the rollers of the exhaust cage;  $\omega_{dv\_kl\_kor}$  – correction of the rotation speed of the engine of the exhaust cage;  $W_{ek}(s)$  – the transfer function of the cage electric drive;  $M_{s\_p}$  – static load moment from rolling;  $M_{dv\_kl}$  – moment of the engine of the exhaust cage;  $M_{s\_σ}$  – the static load moment from the cage tension, applied to the cage motor shaft;  $J_{kl}$  – moment of inertia of the exhaust cage;  $K_{ms\_σ}$  – the proportionality factor between the specific tension of the rolling stock and the static load moment of the cage motor from it;  $K_{kl}$  – structural coefficient of the output cage;  $V_{v\_kl}$  – linear speed of the rollers of the output cage;  $s_{op0}$  – the coefficient of advance of the rolling stock in the discharge cage in the absence of front tension of the rolling stock;  $k_{s\_σ}$  – the coefficient of influence of the front tension of the rolling stock on the coefficient of advance of the rolling stock in the gauge of the cage;  $V_{p\_kl}$  – linear rolling speed at the exit from the cage;  $V_{p\_m}$  – the linear speed of the rolling stock at the point of its contact with the surface of the skein;  $E_u$  – the weighted average value of the modulus of elasticity;  $L_{p\_kl \leftrightarrow m}$  – the length of the unstressed rolling stock between the winder and the cage at the initial moment of time;  $k_{m\_σ}$  – the coefficient of influence of rolled sheet tension on the static load moment of the winder motor;  $R_{n\_m}$  – rolling radius;  $W_{m\_s}(s)$  – the transfer function of the roller tension regulator by correcting the rotation speed of the exhaust

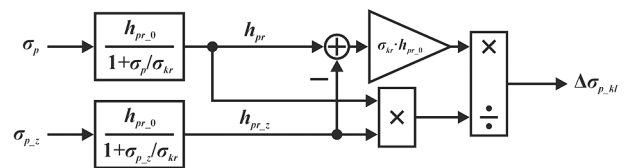


Fig. 1. The structure of the comparison node of the actual and specified specific stresses in the rolling stock along the arrow of its deflection

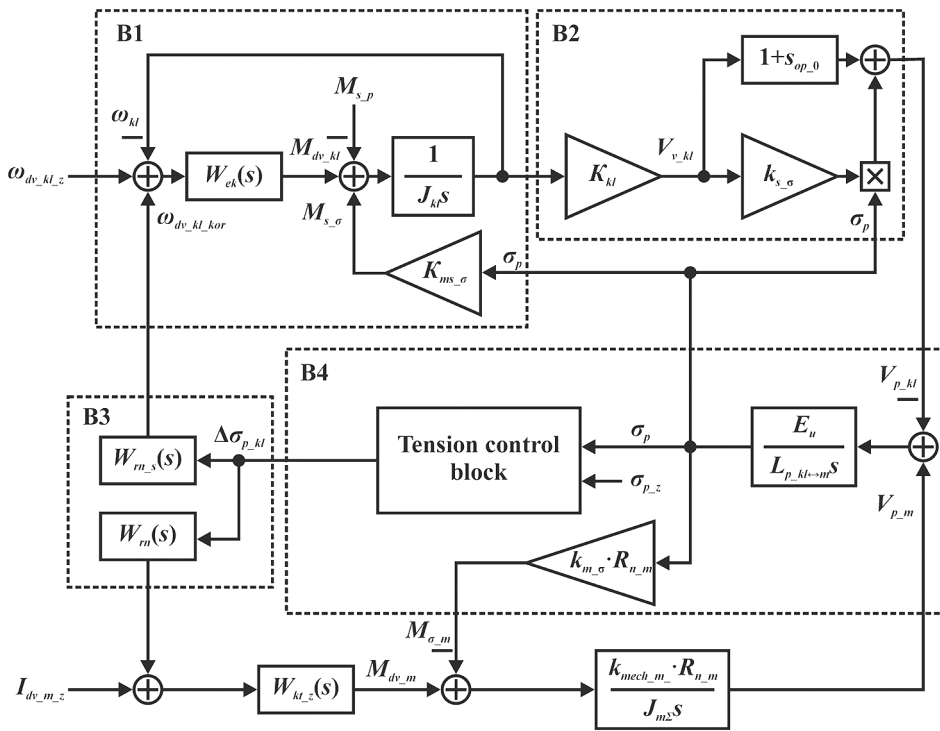


Fig. 2. The structure of the complex model of the outlet cage-winder area with the contours of the roll tension correction for the outlet cage

cage motor;  $W_m(s)$  – the transfer function of the roll tension regulator by correcting the motor current task winders;  $I_{dv\_m\_z}$  – set current of the winder motor;  $W_{kl\_z}(s)$  – the transfer function of the current circuit regulator of the winder electric drive;  $M_{dv\_m}$  – torque of the winder motor;  $M_{\sigma\_m}$  – the load moment from the tension applied to the winder motor;  $k_{mech\_m}$  – esign coefficient of winding mechanisms;  $J_{m\Sigma}$  – the total moments of inertia of the winder and bobbin mechanisms, applied to the winder electric motor shaft.

From the beginning, each of the contours of control of rolled sheet tension was analyzed separately.

The elements of the tension regulation circuit behind the output cage due to the correction of the winding current having been isolated from it, the scheme is obtained (Fig. 3, a). After this scheme is brought to the canonical form (Fig. 3, b) and transformation, the estimated structural diagram of the circuit for regulating the tension of rolled products is obtained, which is shown in Fig. 3, c.

Coefficients in the diagram (Fig. 3, b) are

$$K_V = \frac{D_{n\_m}}{2 \cdot J_{m\Sigma} \cdot i_{rm}};$$

$$T_\Psi = \sqrt{\frac{1}{K_V \cdot K_\sigma \cdot K_{ms_\sigma}}} = \frac{\pi}{16} \cdot \frac{D_{n\_m}^2 \cdot D_p^2}{i_{rm}^2 \cdot J_{m\Sigma}} \cdot \frac{E_{u_{kl \leftrightarrow m}}}{L_{p_{kl \leftrightarrow m}}};$$

$$K_{ms_\sigma} = \frac{\pi}{8} \cdot \frac{D_{n\_m} \cdot D_p^2}{i_{rm}};$$

where  $K_V$  is the proportionality factor that takes into account the influence of the linear speed of rolling;  $i_{rm}$  is gear ratio of the winder reducer;  $T_\Psi$  is the equivalent time constant of the technological control object;  $K_\sigma$  is the proportionality factor that takes into account the influence of the current rolling tension;  $K_{ms_\sigma}$  is the proportionality factor between the specific tension of the rolling stock and the static load moment of the cage motor from it;  $E_{u_{kl \leftrightarrow m}}$  is the weighted average value of the modulus of elasticity.

Neglecting the small time constant of the winder current circuit and taking the current-invariant transfer function of the

winder motor as a proportional link with the coefficient  $K_m$ , we obtain the transfer function “winder motor current-specific tension of the rolling stock”  $W_{1-\sigma}(s)$

$$W_{1-\sigma}(s) = K_m \cdot \frac{K_V \cdot K_\sigma}{1 + \frac{K_V \cdot K_\sigma}{s} \cdot K_{ms_\sigma}} = \frac{K_m}{K_{ms_\sigma} \cdot s^2 + 1} = \frac{K_\Psi}{T_\Psi^2 s^2 + 1}.$$

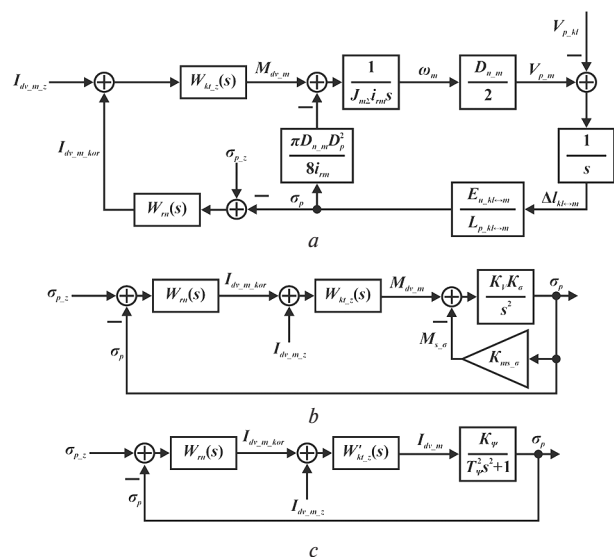


Fig. 3. Structural diagram of the circuit for regulating the tension of the rolling stock in the section of the winder – the cage due to the correction of the winding current: a – initial; b – reduced; c – calculated



The equivalent amplification factor and time constant of the technological control object are equal to

$$K_{\Psi} = \frac{K_m}{K_{ms_{\sigma}}} = \frac{8 \cdot i_{rm} \cdot K_{m_{1z}}}{\pi \cdot D_{n_m} \cdot D_p^2};$$

$$T_{\Psi} = \sqrt{\frac{1}{K_V \cdot K_{\sigma} \cdot K_{ms_{\sigma}}}} = \sqrt{\frac{16 \cdot i_{rm}^2 \cdot J_{m\Sigma} \cdot L_{p_{kl \leftrightarrow m}}}{\pi \cdot D_{n_m}^2 \cdot D_p^2 \cdot E_{u_{kl \leftrightarrow m}}}} =$$

$$= \frac{4 \cdot i_{rm}}{D_{n_m} \cdot D_p} \cdot \sqrt{\frac{J_{m\Sigma} \cdot L_{p_{kl \leftrightarrow m}}}{\pi \cdot E_{u_{kl \leftrightarrow m}}}}.$$

From Fig. 3 we can see that the technological object of control in the loop of regulating the tension of the rolling stock in the section of the winder-cage due to the correction of the winding current is a conservative link due to the presence of internal feedback loops. This should lead to the fact that the transition process in the technological object of control of the outlet cage-rolling mill-winder will have a clearly expressed oscillatory character, which is gradually damped due to the presence of connections with adjacent circuits through the rolling cage.

In the studies to analyze the influence of this circuit on the transient process, a P-regulator with a gain factor  $K_{kn_r}$  was used as a voltage regulator.

$$W_{rn}(s) = K_{kn_r}$$

The transfer function of the open tension circuit is

$$W_{kn_r}(s) = K_{kn_r} \cdot \frac{1}{2 \cdot T_{\mu_r} s + 1} \cdot \frac{K_{\Psi}}{T_{\Psi}^2 s^2 + 1},$$

where  $T_{\mu_r}$  is the uncompensated time constant of the coil current circuit.

The time constant of the oscillating link can be estimated without separate calculations by the period of oscillation of the tension of the rolling stock without contours of stabilization of the tension of the rolling stock. When modeling the basic winding scheme (without contours), its value was obtained close to 3 s. That is, it is two orders of magnitude higher than the time constant of the closed circuit of the current. Therefore, the relative stability of the roll tension control circuit (damping of tension fluctuations) is ensured only when

$$K_{kn_r} < \frac{8 \cdot i_{rm} \cdot K_m}{\pi \cdot D_{n_m} \cdot D_p^2}. \quad (1)$$

Note that in (1) there is such a value as the diameter of the profile –  $D_p$  and parameters that depend on the current winding moment –  $K_m$  and  $D_{n_m}$ .

The peculiarity of coiling of rolled products is that it is carried out at an almost constant rolling speed, that is, in the first approximation, we can consider  $V_p = \text{const}$ . Based on this it was adopted

$$\omega_m \cdot D_{n_m} = \text{const},$$

or

$$\omega_m \cdot D_{n_m} = \omega_{m(1)} \cdot D_{n_{m(1)}}, \quad (2)$$

where  $\omega_m$  is the winder rotation speed;  $\omega_{m(1)}$  is the rotation speed of the winder when winding the first layer;  $D_{n_{m(1)}}$  is the winding diameter of the first layer.

It is clear that (2) is valid within one profile size.

Another feature of the winder operation is that the winding process takes place in the second zone of the winder operation, that is, in the first approximation, it can be assumed that

$$K_m = K_{m_{1z}} \cdot \frac{\omega_{m_{1z}}}{\omega_m}, \quad (3)$$

where  $K_{m_{1z}}$  is the value of  $K_m$  in the first working zone of the winder;  $\omega_{m_{1z}}$  is the upper limit value of the winder rotation speed when working in the first zone.

Substituting (2, 3) into (1), we have

$$K_{kn_r} < \frac{8 \cdot i_{rm} \cdot K_{m_{1z}}}{\pi \cdot D_{n_{m(1)}} \cdot D_p^2}.$$

Hence, the parameters of the tension regulator should be related only to the profile size of the rolled product being wound.

As for the structure of the model of the control system (Fig. 2), we have isolated the elements of the circuit for adjusting the tension behind the exhaust cage with the correction of the speed of rotation of the exhaust cage rollers, and obtained a scheme (Fig. 4), where  $W_{ks_z}(s)$  is the transfer function of the closed circuit of the speed of the electric drive cages;  $\omega_{kl}$  is rotation frequency of cage rolls;  $D_{kl}$  is diameter of cage rolls;  $V_{v_{kl}}$  is the linear speed of the rollers of the output cage;  $\Delta l_{kl \leftrightarrow m}$  shows increase in the length of the rolled product in the area of the exit cage-winder;  $W_{m_s}(s)$  is the transfer function of the roll tension regulator;  $K_{\omega_{\sigma}}$  is the coefficient of proportionality between the frequency of rotation of the rolls of the cage and the specific tension of the rolling stock in the section of the exit cage – the winder.

This scheme can be simplified by getting rid of the parallel branch in the circuit  $\omega_{kl} \rightarrow V_{p_{kl}}$  containing the multiplicative block.

Based on the data given in the handbook on the theory of rolling, edited by V. I. Zyuzina and A. V. Tretyakov, the value of  $1 + s_{op_0}$  is equal to 1.014, and the value of  $k_{\omega_{\sigma}} \cdot \sigma_p$  at the maximum value of the specific tension of 30 N/mm<sup>2</sup> is equal to  $4 \cdot 10^{-4} \cdot 30 = 0.012$ , that is, it is two orders of magnitude smaller. As a result of the simplification, a calculation scheme was obtained (Fig. 4, b).

This diagram is a traditional circuit diagram of the position of subordinate regulation systems based on the P-regulator. The gain factor of the position regulator  $K_{kn_r}$  is adjusted according to the standard method.

The search for methods of controlling the winder-cage complex, which ensure increased stability of the roll tension both in front of the winder and directly behind the output cage, was carried out by modeling different modes of control of the tension of the rolled product in this area, followed by a comparative analysis of the influence of the control mode on the tension of the rolled product during its winding.

Research was carried out under three main management modes and a combined one:

- winding only with the task of winding tension due to the winding drive current (basic mode);
- winding with the task of winding tension and its correction for the deviation of the actual rolled tension from its value in the steady mode of winding;
- winding with the task of winding tension and correction of the given speed of rotation of the cage drive by the deviation

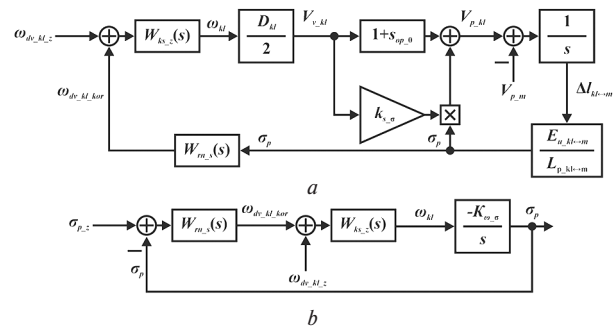


Fig. 4. Structural diagram of the circuit for regulating the tension of the rolling stock in the section of the winder – the cage due to rotation speed correction rollers of the output cage:

a – initial; b – calculated

of the actual rolled tension from its value in the steady mode of winding;

d) winding with the task of winding tension and correction of both the task of rolling tension and the set speed of rotation of the cage drive by the deviation of the actual rolling tension from its value in the steady mode of winding.

According to the control modes and the general structural diagram of the winding model with control loops (Fig. 2), the gain coefficients of the tension regulator and the position regulator with the basic scheme  $K_{kn,r}=0, K_{kp,r}=0$ , with the scheme with winding current correction  $K_{kn,r} \neq 0, K_{kp,r}=0$ , with the scheme with the correction of the speed of rotation of the rollers of the exhaust cage  $K_{kn,r}=0, K_{kp,r} \neq 0$ , with the scheme with the correction of both the winding current and the rotation speed of the rollers of the exhaust cage  $K_{kn,r} \neq 0, K_{kp,r} \neq 0$ .

The model of the control system for winding rolled products with a Garrett-type winder was adjusted to the profile size of a circle with a diameter of 16 mm.

The task of the rotation speed of the output cage rolls was set according to the calibration table of the given profile size, the task of the winder current – in accordance with the recommendations for managing the production of graded rolled products in coils for the operator PU-5 – the post of managing the section of graded winders of the small-grade wire mill DSDS 250/150-6 of the enterprise PJSC “ArcelorMittal Kryvyi Rih”.

The main simulation results are given in the Table.

Above all, the tension of the rolled product was analyzed directly behind the output cage in the mode of winding the rolled product according to the basic scheme. First of all, it was determined that the nature of the transition process during stacker reversal fully corresponds to the results of the analytical analysis of the complex model of the discharge cage-winder area – it has a pronounced oscillatory character with a maximum value of tension close to the lower limit of plastic deformation of rolled products in the discharge cage rolls and a minimum value so that it ensures a minimum satisfactory density of adhesion of the rolled product to the body of the skein. It should be noted that the recommendations for the PU-5 operator are determined by the last factor, according to which the given current of the winder corresponds to the value of the static tension of the rolled steel in front of the winder and behind the cage of approximately 10 N/mm<sup>2</sup>, which is almost two times higher than its rational value 4–6 N/mm<sup>2</sup>.

Secondly, the maximum value of the tension after reversing the stacker in its lower position is less than after reversing the stacker in its upper position and lies in the middle of the zone of elastic-plastic deformation. This is due to the fact that the length of the roll between the output cage and the point of its first contact with the skein body depends on the position of the stacker.

From the given analysis of the change in the tension of the rolled steel during winding according to the basic control mode, it can be concluded that even with careful adjustment of the winder current, local contractions of the profile of the

rolled steel being wound can occur on the verge of exceeding the tolerance limits of its cross-sectional dimensions.

In general, the results of the analysis of rolled steel winding in the mode of winder current stabilization with its correction for the deviation of the deflection of the rolled steel at the output cage from the specified value are the same as when winding rolled steel according to the basic scheme, but the maximum value is slightly less, and the minimum value is slightly more than when winding according to the main scheme. Therefore, when correcting the specified current of the winder for the deviation of the deflection of the rolled product behind the output cage from the specified value, a slight decrease in the value of local indentations of the profile of the rolled product should be expected, but not their elimination.

A radically different picture of rolled steel winding with the task of winding tension and correction of the specified speed of rotation of the outlet cage drive by deviation of the actual tension of the rolled steel from its value in the constant winding mode. In this case, the maximum tension of the rolled steel lies near the lower limit of the zone of elastic-plastic deformation, and the minimum value of the tension lies slightly below the value of the specified tension and above the rational value of the tension, which ensures a tight fit of the rolled turns to the body of the coil. This makes it possible to reduce the tension of the rolling stock between the output cage and the winder to rational values, which will provide conditions for a reliable reduction of the value of the maximum tension to the level that corresponds to the upper limit of the elastic deformation of the rolling stock. Another positive result of coiling rolled steel in this mode of controlling the tension of the rolling stock in the area of the output cage of the winder compared to the basic control mode and the winding mode with the task of winding tension and its correction according to the deviation of the actual tension of the rolled steel from its value in the constant winding mode is an almost threefold reduction in the time of the transition process when reversing the stacker.

Thus, coiling of rolled steel in the control mode with the task of winding tension and correction of the specified speed of rotation of the output cage drive to deviate the actual tension of the rolled steel from its value in the constant winding mode makes it possible to almost completely get rid of the local tightening of the profile of the rolled steel, which is associated with a dynamic increase in the tension of the rolled steel when reversing the stacker.

The results of the simulation of the control mode with the task of winding tension and correction of both the task of rolling tension and the set speed of rotation of the cage drive in terms of the deviation of the actual tension of the rolled material from its value in the constant winding mode are not much different from the results of the simulation of winding in the control mode with the task of winding tension and correction at the given speed of rotation of the drive of the output cage on the deviation of the actual tension of the rolled metal from its value in the steady winding mode, which allows once again confirming the low efficiency of the control circuit with the correction of the winder current to minimize dynamic changes in the tension of the rolled metal in the area of the output cage – the winder.

In general, it can be concluded that the method of correcting the speed of rotation of the output cage rolls is significantly more effective compared to the method of correcting the winding current.

It should be noted that an increase in the roll tension when the stacker reverses in the basic mode of winding control is accompanied by a dynamic increase in the rotation frequency of the output cage roll drive (the roll “pulls the cage”), which leads to an increase in the linear speed of the roll at the exit of the cage. An additional component of the growth of the linear velocity of the rolling stock is related to the growth of the roll advance ratio in the cage (Fig. 4, a). In parallel, there is a process of a decrease in the speed of rotation of the winder drive.

Table

The main parameters that characterize the rolling process on a Garrett-type winder

Parameter	Mode			
	<i>a</i>	<i>b</i>	<i>c</i>	<i>d</i>
$\sigma_{p-z}, \text{ N/mm}^2$	10	10	10	10
$\sigma_{\min}, \text{ N/mm}^2$	2.62	3.44	8.76	7.67
$\sigma_{\max}, \text{ N/mm}^2$	28.8	24.8	20.54	18.9
$\omega_{kl}, \text{ rad/s}$	52.78	52.76	53.09	53.22
$\Delta\omega_{\max}, \%$	1.5	1.46	2.1	2.35

The increase in tension is completed when the linear speed of the rolling stock at the exit of the cage is equal to the linear speed of the rolling stock at the point of its first contact with the coil. The introduction of the roll tension control circuit in the outlet cage-winder section through the correction of the rotation speed of the outlet cage rolls allows you to speed up this process and achieve equilibrium due to the increase in the linear velocity of the rolled products due to the increase in the frequency of rotation of the outlet cage rolls and the decrease in the component due to the increase in the tension of the rolled products.

As a consequence, there is a greater deviation of the rotation frequency of the exhaust cage rolls from a constant value when controlling the tension due to the correction of the rotation frequency of the exhaust cage rolls than when working according to the basic scheme or according to the scheme with the winding current correction circuit.

It should be noted that the introduction of an additional circuit for controlling the tension of the rolling stock, closed through the output cage, leads to the appearance of two control channels for regulating the tension of the rolling stock due to the assignment of the winding current and due to the stabilization of the deflection of the rolling stock by adjusting the speed of rotation of the rolls of the cage.

When the tasks for rolling tension on both control channels coincide, they do not compete with each other.

In order to clarify the interaction of the control channels when there is a mismatch between them in the tasks for the tension of the rolling stock, a simulation was carried out of a situation where the winding current of the winder sets a tension of 10 N/mm<sup>2</sup>, which corresponds to a deflection of 50 mm, and a tension corresponding to a deflection of 70 mm was set in the tension stabilization circuit.

The simulation results showed that the averaged specific tension of the rolling stock in the near-steady state practically did not change compared to the previously considered cases. In contrast to the value of the rotation speed of the rolls, which increased by 0.5 %.

Thus, it can be concluded that when controlling the tension of the rolling stock behind the output cage through the correction of the speed of rotation of its rolls in the case of a mismatch of the specified tension values, the actual amount of tension of the rolled product in the section of the winder – the cage will be determined by the specified current of the winder, and the speed of rotation of the rolls of the output cage will differ from the given base value.

It should also be noted that such a steady deviation of the rotation speed of the output cage rolls from the base value will lead to a change in the technologically regulated rolling speed, and, therefore, the productivity of the rolling mill. It is obvious that this effect is negative and inadmissible from the point of view of technology. Therefore, the implementation of such a control method requires the adoption of additional technical solutions to exclude this effect, for example, the circuit for correcting the frequency of revolutions of the cage rolls is turned on at the moment of giving a command to the reverse stacker and is turned off at the end of the transition process.

The most rational scheme of the interaction of the circuit for controlling the tension of the rolling stock due to the correction of the winding current and the circuit for controlling the tension of the rolling stock due to the correction of the speed of rotation of the rolls of the outlet cage is a scheme in which the first circuit is constantly turned on, and the second circuit is turned on at the moment of reverse of the stacker and is turned off when the tension of the rolled product is reached behind the outlet cage of a value that is smaller than the upper limit of the zone of elastic deformation of the rolled product (deflection), e.g. 10 N/mm<sup>2</sup>.

#### Conclusions.

1. With the existing winding scheme, the transient process of rolled sheet tension in the area of the outlet cage – Garrett

winder caused by the reverse of the stacker has an oscillatory character with the tension reaching the upper limit in the zone of elastic-plastic deformation. As a result, even with careful adjustment of the winder current, local contractions of the profile of the rolled product being wound may occur on the verge of exceeding the tolerance limits of its cross-section.

2. When winding rolled products in the current stabilization mode of the winder with its correction for the deviation of the deflection behind the discharge cage from the specified value, the transient process in terms of tension has the same character as when winding rolled products according to the basic scheme with a slight decrease in the deviations of its tension from the specified value. Therefore, when the winder current is corrected for the deviation of the deflection of the rolled product behind the output cage from the specified value, a decrease in the value of local indentations of the profile of the rolled product should be expected, but not their elimination.

3. Winding of rolled products in the current stabilization mode of the winder with the correction of the rotation speed of the output cage by deviation of the deflection of the rolled products behind the output cage from the specified value eliminates the oscillatory nature and reduces the time of the transition process on its tension, which is caused by the reverse of the stacker. This control mode makes it possible to reduce the task of tensioning the rolling stock between the output cage and the winder to rational values and almost completely get rid of the local tightening of the rolling stock profile.

4. The application of the method of controlling the actual tension of the rolled steel according to its free deflection behind the output cage to improve the rolling tension control system during its winding with a winder allows solving the problem of minimizing dynamic changes in the tension of the rolled steel behind the output cage to technologically acceptable values.

5. To prevent a conflict between the channel for setting the tension of the rolling stock due to the setting of the current of the winder electric drive and the circuit for correcting the speed of rotation of the output cage for the deviation of the current deflection of the rolled product behind the output cage from its set value, it is advisable to turn on this circuit at the moment of reversing the stacker and turn it off when the deflection of the rolled product increases to values corresponding to the upper limit of the zone of elastic deformation of the rolled product, for example, 10 N/mm<sup>2</sup>.

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## Мінімізація динамічних змін натягу сортового прокату за випускною кліттю при його виробництві в мотках

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**Мета.** Обґрунтування технічних рішень щодо зменшення амплітуди та зменшення тривалості динамічних змін натягу прокату на виході випускної кліті при переході до намотування нового шару мотка до прийнятного рівня, з точки зору його впливу на результуючий профіль прокату, за рахунок керування частотою обертання випускної кліті.

**Методика.** Проведене дослідження базувалося на комплексній моделі процесу намотування прокату моталкою типу Гаррета й натягу прокату на ділянці випускна кліть—моталка. Задля контролю фактичної величини

натягу на виході випускної кліті запропоновано використовувати величину вільного прогину прокату безпосередньо за кліттю. Дослідження проводилися шляхом моделювання процесу намотування прокату за базовою схемою керування та схемами керування, що передбачають вплив на привід, як моталки, так і випускної кліті, за фактичною величиною натягу у різних комбінаціях з подальшим аналізом і порівнянням отриманих результатів.

**Результати.** Встановлено, що корекція по відхиленню фактичного натягу прокату на ділянці чистова кліть—моталка від заданої величини струму змотування електропривода моталки практично не усуває ривки натягу прокату при переході на намотування наступного шару й коливальну форму перехідного процесу, які характерні для базової схеми змотування прокату. У свою чергу корекція частоти обертання приводу валків випускної кліті знижує амплітуду ривка натягу прокату майже вдвічі, з одночасним скороченням часу перехідного процесу й перерегулювання при переході на намотування нового шару мотка.

**Наукова новизна.** Уперше показано, що введення контуру керування натягом прокату шляхом корекції швидкісного режиму прокатки випускної кліті забезпечує мінімізацію динамічних змін натягу прокату при переході до намотування нового шару мотка та зниження ймовірності локального утягнення профілю прокату.

**Практична значимість.** Використання описаних технічних рішень у системі керування ділянкою намотування сортового прокату дрібносоротно-дротяного стану ДСДС 250/150-6 ПАТ «АрселорМіттал Кривий Ріг» забезпечує підвищення товарних властивостей мотка прокату, що виробляється на прокатному стані.

**Ключові слова:** моталка, натяг прокату, керування струмом змотування, керування швидкісним режимом прокатки

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