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DYNAMIC MODEL OF COLD STRIP ROLLING

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A dynamic model of the cold rolling process at the continuous rolling mill that combines the model of the electromechanical system and the model of the deformation zone has been developed. The paper presents the results of the study of kinematic parameters, force and energy parameters of the deformation zone with regard to the fluctuating nature of the process variables and to the dynamic processes running in the electromechanical system. It is shown that the variations in the stated parameters are of fluctuating unsteady nature, which has an adverse effect on operation of equipment and quality of finished products.

Key words: cold rolling, strip, electromechanical system, dynamic model, deformation zone

INTRODUCTION

Dynamic loads arise in the electromechanical systems of the working stands during strip rolling at continuous wide-strip cold rolling mills. This occurs due to variations in the process parameters and strip thickness, as well as due to torsional vibrations in the drive system. Unsteady dynamic loads result in electric power losses. The dynamics of power losses is not always analyzed by specialists and is not taken into account in designing the cold rolling process and optimizing the existing process solutions.

Most mathematical models for cold rolling processes and methods for calculation of geometry parameters of the deformation zone, process parameters and energy-force parameters are based on statistical models [1-3] that do not consider the dynamic nature of the processes in real manufacturing environment.

Modeling the dynamic processes that take place during continuous cold rolling is a rather complicated task, with only some of its aspects being described in the technical literature. The dynamic models for cold rolling described in papers [4, 5] are process control models intended for designing controllers without prediction of stresses, strains and loads in the working stands. Paper [6] touches upon the mathematical description of the electromechanical system of the cold rolling stand for the purpose of investigating dynamic loads in the electrical drive of the stand without regard to the influence of the deformation zone (contact interaction between the strip and the rolls).

Taking into account the multi-factor nature of the process and complex interrelationships between the electromechanical systems of the stands of the continuous cold rolling mill, further integrated development of the thin-sheet rolling process is impossible without development of a model of the cold rolling process that would consider its dynamic and unsteady nature.

The work is focused on development of a mathematical model of the cold rolling process that would reflect dynamic interrelationships between the torsional system of the driveline, the stand system and the deformation zone with a view to investigate how dynamic loads influence the energy-force parameters of the cold rolling process and to design an energy-efficient technology for cold rolling.

MODEL DESCRIPTION

In order to develop a mathematical representation of the cold rolling process at the continuous mill the following objects were considered: electromechanical systems of the stands EMS (including automated electric drives, gear boxes and stands), deformation zones. The structural diagram of the mathematical model for cold rolling at the continuous mill stands is shown in Figure 1. In Figure 1 the following symbols: U_{i-1}, U_i, U_{i+1} – voltage across the armature winding of the motor of the stand (i-1), stand i and stand (i+1); ω_{ri-1}, ω_{ri}, ω_{ri+1} – angular velocity of rotation of the work roll body of the stand (i-1), stand i and stand (i+1); T_{ri-1}, T_{ri}, T_{ri+1}, – torque required for the rolling process to take place in the stand (i-1), stand i and stand (i+1); υ_0 – velocity of the workpiece; h_0 – thickness of the workpiece; σ_0 – strip tension at the mill entry; υ_{i-1}, υ_i, υ_{i+1} – strip velocities at the exit from stand (i-1), stand i and stand (i+1); h_{i-1}, h_i, h_{i+1} – strip thicknesses at the exit from stand (i-1), stand i and stand (i+1); σ_{i-1}, σ_i, σ_{i+1} – strip tension.

The inputs of the model are the electric drives' input control voltages, the outputs of the model are strip velocity at the exit from the rolls and tension. The model of the deformation zone has four inputs and for outputs that connect the model with the main drive and with the adja-

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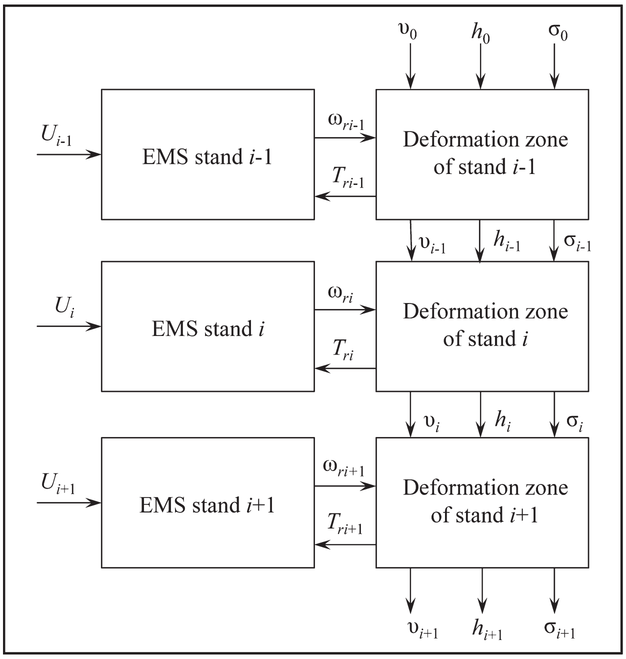

Figure 1 Structural diagram of the mathematical model of the cold rolling process

cent stands through interstand spaces. The impact on the motor voltage is transmitted to the input of the deformation zone through roll speed with torque feedback.

Mathematical description of the deformation zone of working stand i is based on the elastoplastic model, according to which a strip is treated as a thin elastoplastic body and rolls are regarded as massive elastic bodies [7, 8].

The output coordinate of the model of the deformation zone going to the electric driveline (Figure 1) is the torque T_{ri}, required for the rolling process in stand i to take place:

$$T_{ri} = T_{roli} + T_{fr.bi} + T_{bri} + T_{tensi}, \tag{1}$$

where T_{roli} – rolling torque; $T_{fr.bi}$ – friction torque in the work roll bearings; T_{bri} – torque required for rotation of non-driven backup rolls; T_{tensi} – torque arising from the difference between the backward tension force and forward tension force.

The rolling torque is calculated with the use of the formula, which does not include empirical coefficients of the arm of the rolling force:

$$T_{roli} = \frac{P_{roli}}{\omega_{ri}}, \tag{2}$$

where P_{roli} – rolling power calculated with consideration for the rolling work at each of the elastic and plastic sections of the deformation zone;

The friction torque in the work roll bearings is determined by drawing a diagram of forces and torques in the four-high stand with driven work rolls and analysis of the diagram:

$$T_{fr.bi} = R_{ch\Sigma i} \cdot \rho_{wr}, \tag{3}$$

where $R_{ch\Sigma i}$ – sum of horizontal forces acting on the work roll neck as reactions arising in the chocks and bearing supports under the influence of strip tensions and other working loads; ρ_{wr} – radius of the friction circle in the work roll bearings.

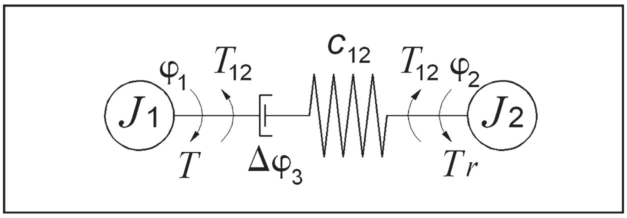

Figure 2 Analytical model of dual-mass system

The torque required for rotation of non-driven backup rolls:

$$T_{bri} = P_{bri} \cdot d_{wr}, \tag{4}$$

where P_{bri} – interroll force acting from the driven work roll on the non-driven backup roll; d_{wr} – distance from the work roll axis to the line of force P_{bri}.

The torque arising from the difference between the backward tension force and forward tension force:

$$T_{tensi} = \frac{N_i - N_{i\text{-}1}}{2} R, \tag{5}$$

where R – work roll body radius; $N_{i\text{-}1}$, N_i – strip backward tension force and forward tension force, respectively.

The model of the electromechanical system that considers all inertia elements, all relationships between them and effective loads is rather complicated. Therefore, the subject of investigation is represented with the aid of an analytical model - the system equivalent in terms of energy and reflecting the most important dynamic properties.

Analysis of frequency characteristics of the main drivelines of the stands of continuous thin-sheet rolling mills, as well as the results of the experimental studies presented in papers [9] have shown that a dual-mass analytical model for the main line of the stand represents the actual transient process with an accuracy sufficient for practical purposes.

At analytical model given in Figure 2, electric drive of the top or bottom roll describes dual-mass system with elasticities with consideration of backlashes in the transmissions.

In simple terms, the electromechanical system operation may be described as follows:

$$T - T_r = J \cdot \frac{d\omega}{dt}, \tag{6}$$

where T – electromagnetic torque of the motor; T_r – motion resistance torque; ω – motor shaft speed; J – joint inertia of the armature and the load.

According to the accepted analytical model (Figure 2), the motion of the reduced masses in relation to the equilibrium state is described with a differential equation system:

$$\begin{cases} T - T_{12} = J_1 \cdot \dfrac{d\omega_1}{dt}; \\ T_{12} - T_r = J_2 \cdot \dfrac{d\omega_2}{dt}; \\ T_{12} = c_{12}(\varphi_1 - \varphi_2 - \Delta\varphi_3 / 2 \ \text{ at } |\varphi_1 - \varphi_2| < \Delta\varphi_3 / 2; \\ T_{12} = 0 \ \text{ at } |\varphi_2 - \varphi_1| \geq \Delta\varphi_3 / 2, \end{cases} \tag{7}$$

where T_{12} – elastic interaction torque; c_{12} – reduced stiffnesses of mechanical elastic linkages; ω_1, ω_2 – motor shaft speed of the first and second masses; J_1, J_2 – joint inertia of the first and second masses; φ_1, φ_2 – angles of rotation of the first and second masses; $\Delta\varphi_3$ – backlash in mechanical transmissions.

In order to consider the influence of transient processes in the electric drive on the mode of dynamic loading in the electromechanical system of the stand a description of separately excited DC motor by differential and algebraic equations in absolute units is introduced:

$$\begin{aligned} u &= e + R \cdot i + L \cdot \frac{di}{dt}; \\ T &= C_T \cdot F \cdot i; \\ E &= C_\omega \cdot F \cdot \omega, \end{aligned} \tag{8}$$

where u – voltage across the armature winding of the motor; e – armature electromotive force (EMF); i – armature current; F – flux produced by the excitation winding; R – active resistance of the armature circuit; L– inductance of the armature circuit; C_ω – coupling coefficient between the velocity and EMF; C_T – coupling coefficient between the armature current and electromagnetic torque.

RESULTS AND DISCUSSION

The dynamic model of the cold rolling process was developed in the MATLAB/Simulink system. Its adequacy to the subject of investigation was assessed based on the results of comparison of the rolling process parameters obtained via modeling with those obtained through oscillography at the real 5-stand cold rolling mill 1700.

Figure 3a shows a graph representing the roll force variation along the strip length that was obtained from experimental rolling as per the rolling schedule (Table 1) for stand No. 2. Figure 3b shows a similar graph obtained by calculations with the use of the developed mathematical model. The results of comparison of the experimental and calculated data bring us to the conclusion that the model allows predicting not only the force value, but its behavior with high accuracy. Similar checks of the mathematical model adequacy were performed for the other stands of the mill.

Table 1 **Process parameters for the cold rolling schedule for 0,9 mm thick and 1 075 mm wide strip at the 5-stand mill 1700 at the production site of PAO Severstal**

Stand No.	υ_i / m/s	h_{i-1} / mm	h_i / mm	ε_i / %	N_{i-1} / kN	N_i / kN
1	7,71	3,0	2,22	26,06	111	329
2	10,58	2,22	1,62	27,1	329	271
3	14,24	1,62	1,2	25,73	271	226
4	18,24	1,2	0,94	21,98	226	186
5	19	0,94	0,9	3,95	186	44

Note. ei – individual percent reduction of the strip in stand i.

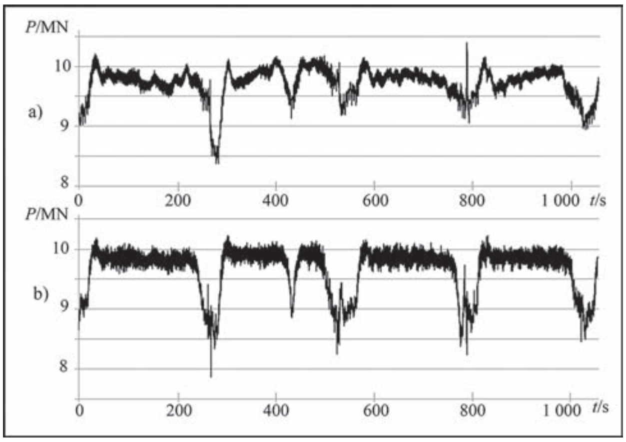

Figure 3 Graphs representing the roll force variation *a*) actual values; b) calculated values

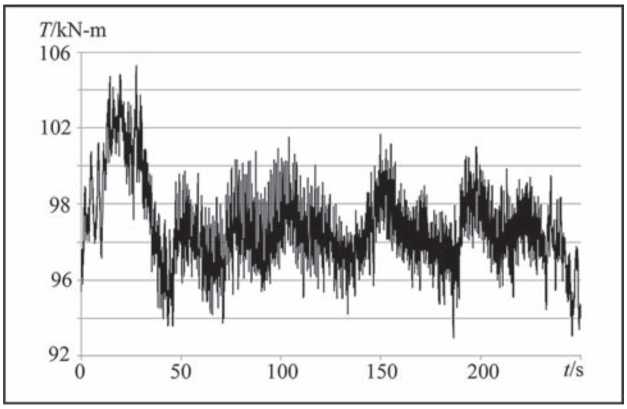

Figure 4 Graph representing variation of the rolling torque along the strip length

Analysis of the results of modeling the rolling torque (Figure 4) shows that the highest peak values during the steady-state rolling process correspond to the periods when a strip with a strong crown is being rolled, in which case the variation range may be as high as 10 – 15 %.

CONCLUSION

A dynamic model of the cold rolling process that combines the model of the electromechanical system of the rolling mill and the model of the deformation zone and considers their interrelation has been developed.

Modeling and analysis of energy-force parameters of the deformation zone with regard to the dynamic processes running in the electromechanical system and with consideration of the variations of the process parameters have been performed. It is shown that the variations in the stated parameters are of fluctuating unsteady nature, which should be taken into account in the technological process adjustment and control.

The results obtained are intended to be used for identification of the causes of adverse vibrations in the working stands, development of the ways to decrease dynamic loads and reduce energy losses during cold rolling, prediction of geometry characteristics of finished products, as well as for development of fundamentally new procedures for adjustment and control of the rolling process and equipment.

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List of symbols, abbreviations and acronyms

EMS – electromechanical system of the stand;
U_{i-1}, U_i, U_{i+1} – voltage across the armature winding of the motor of the stand (i-1), stand i and stand (i+1);
ω_{ri-1}, ω_{ri}, ω_{ri+1} – angular velocity of rotation of the work roll body of the stand (i-1), stand i and stand (i+1);
T_{ri-1}, T_{ri}, T_{ri+1}, – torque required for the rolling process in the stand (i-1), stand i and stand (i+1);
υ_0 – velocity of the workpiece;
h_0 – thickness of the workpiece;
σ_0 – strip tension at the mill entry;
υ_{i-1}, υ_i, υ_{i+1} – strip velocities at the exit from stand (i-1), stand i and stand (i+1);
h_{i-1}, h_i, h_{i+1} – strip thicknesses at the exit from stand (i-1), stand i and stand (i+1);
σ_{i-1}, σ_i, σ_{i+1} – strip tension;
T_{roli} – rolling torque;
$T_{fr.bi}$ – friction torque in the work roll bearings;
T_{bri} – torque required for rotation of non-driven backup rolls;
T_{tensi} – torque arising from the difference between the backward tension force and forward tension force.
P_{roli} – rolling power calculated with consideration for the rolling work at each of the elastic and plastic sections of the deformation zone;
P_{bri} – interroll force acting from the driven work roll on the non-driven backup roll;
d_{wr} – distance from the work roll axis to the line of force P_{bri};
R – work roll body radius;
N_{i-1}, N_i – strip backward tension force and forward tension force;
T – electromagnetic torque of the motor;
ω – motor shaft speed;
J – joint inertia of the armature and the load;
T_{12} – elastic interaction torque;
c_{12} – reduced stiffnesses of mechanical elastic linkages;
ω_1, ω_2 – motor shaft speed of the first and second masses;
J_1, J_2 – joint inertia of the first and second masses;
φ_1, φ_2 – angles of rotation of the first and second masses;
$\Delta\varphi_3$ – backlash in mechanical transmissions;
u – voltage across the armature winding of the motor;
e – armature electromotive force (EMF);
i – armature current;
F – flux produced by the excitation winding;
R – active resistance of the armature circuit;
L– inductance of the armature circuit;
C_ω – coupling coefficient between the velocity and EMF;
C_T – coupling coefficient between the armature current and electromagnetic torque\$
ε_i – individual percent reduction of the strip in stand i.

Note: The person responsible for the translation of the paper into the English language is Natalia Skrobot, Cherepovets, Russia.