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SHEET MILL CONTROL IN STEEL STRIP HOT ROLLING

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ABSTRACT

Research results and technology solutions of strip quality control during hot rolling are presented. Examples of science-based technical solutions for the production of hot strips in the mills 2000 and 1700 have been given.

Keywords: hot rolling, strip quality, metal temperature, rheological and geometric parameters, control, simulation.

INTRODUCTION

The development of industries that use steel products demands from manufacturers high accuracy of dimensions and forms (flat surface accuracy), specified and stable properties of hot-rolled steel strips. Over the years we have gained a great scientific and technical potential and production experience to ensure the effectiveness of the strip rolling process in various units. However, despite the large amount of theoretical and experimental work with a purpose to improve sheet rolling, the problem of mill control and automation in order to enhance rolling stability and obtain high-quality strips remains urgent.

Ensuring stable rolling process and obtaining the desired strip quality (thickness, profile, width, flatness, yield strength and ultimate strength) as well as the rolled work piece deformability (plasticity) require initial adjustment and control of the mill when rolling each strip. The complexity of the problem is related to a number of the sheet hot rolling process features. It is, above all, the need for assessment and control of metal deformability, identification of criteria and priorities of the initial mill adjustment, as well as essential interdependence of process parameters and strip quality factors, which must be set up and taken into account in control.

Formulation of the problem

Hot strip rolling is carried out in modern sheet mills (SM) which include furnaces for metal reheating, roughing and finishing trains for rolling and a coiling machine for coiling the strip into a roll. Considering the sheet mill as a control object one can distinguish (Fig. 1) the following main areas of metal processing in the line “slab heating – hot strip rolling” [1]:

1) reheating furnaces;
2) furnace roller table;
3) roughing train;
4) run-up table;
5) finishing train;
6) run-out table;
7) coiling machines.

The parameters coordinating the operation of these sectors are temperature and thickness, respectively: 1) T_{sl} and H_{sl} of the slab at the furnace outlet; 2) T_b and H_b of the semi-finished rolled product at the roughing train outlet; 3) T_f and H_f of the semi-finished rolled product at the run-up table outlet (at the finishing train inlet).

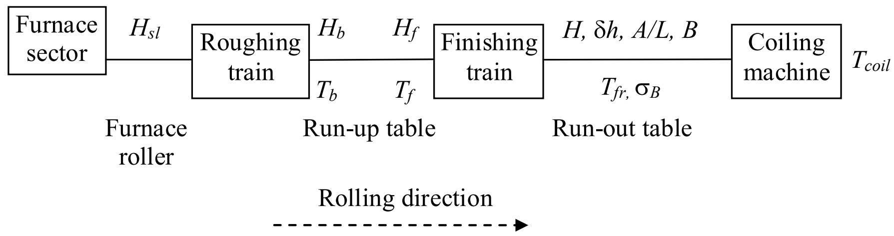

Fig. 1. Diagram and parameters of SM rolling process.

These coordinating parameters are output parameters for a corresponding sector and input parameters for the next rolling sector. The final rolling temperature T_{fr}, thickness h, polythickness δh, flat surface accuracy A/L, width B, ultimate strength σ_B, strip coiling temperature T_{coil} at the finishing train outlet are output parameters that determine the quality of hot rolled metal. On the run-up table the semi-finished roll product thickness does not change, i.e $H_b = H_f$.

The main parameters of the deformation zone, which, when actuated, provide required geometrical and rheological (plastic) rolling characteristics, include the following: the shift of the screwdown mechanism ΔS, force change in forced bending or rolls shear Q, change in the tension F_t, thickness h_0 and profile δh_0 of the rolled piece at the stand inlet, the strip temperature T, rolls profiling (including machine, heat and wear profiling), rolled piece width at the stand inlet B_0, rolling speed V, variations in the strip chemical composition.

The interaction of various rolling parameters influences the performance of the main control channels of the strip size, flatness, mechanical properties and deformability, which are presented in detail in the papers [1, 2].

Specifying the interdependence of the process variables, the systemic influence of control action and interference on the strip quality during sheet rolling allow to make proper control algorithms and efficient control systems.

Control of geometrical parameters at hot strip rolling

The problem of the process control of the strip quality geometric parameters can be solved by selecting and implementing control modes, in consideration of technological constraints.

The main criterion for the strip thickness automatic control system assessment evaluating is adjustment accuracy. The adjustment of the gap between rolls is based on the principle of indirect measurement of the strip thickness in the stand, whereby the change in thickness at the stand outlet, conditioned by the change in the rolling force and the shift of the screwdown mechanism, is described by

$$h_1 = S_0 + P/M_{stand}, \tag{1}$$

where h_1 - the rolled strip thickness; S_0 - the unloaded rolls clearance; P - rolling force; M_{stand} - the stand stiffness coefficient.

Full compensation of the longitudinal polythickness corresponds to the condition:

$$\Delta S_0 = -\Delta P/M_{stand} \tag{2}$$

The method of the strip profile control efficiency assessment by influencing the profiles of the active forming rolls of various mill stands in consideration of constraints in metal flatness and adjustment range is as follows. The efficiency of the influence on the strip profile in various mill stands can be evaluated by the efficiency of the last n stand of the continuous group [1]:

$$\overline{U_i} = \frac{\Delta\delta h_{n(i)}}{\Delta\delta h_{n(n)}} = \frac{[\Delta\delta S_i]\frac{\partial\delta h_i}{\partial\delta S_i}\cdot\prod_{i=1}^{n}\frac{\partial\delta h_i}{\partial\delta h_{0,i}}}{\xi_n\cdot h_n} \tag{3}$$

where $h_{0,i}$ - thickness at the i roll stand inlet, h_i - thickness at the i roll stand outlet, $[\Delta\delta S_i]$ - maximum change in the profile of the active forming rolls in the i roll stand, and if the influence and flatness constraint overlap,

$$[\Delta\delta S_i] = \frac{\xi_i\cdot h_i}{\partial\delta h_i/\partial\delta S_i}$$

A tablet strip can be obtained under the following condition:

$$\left(\frac{\delta h}{h}\right)_{i-1} - \left(\frac{\delta h}{h}\right)_i \le \xi_i , \quad (4)$$

where $\xi_i = \pm(\Delta\delta h / h)_i$ - acceptable mismatch (toward wave (+) or box (-)) of relative strip profiles in adjacent millstands.

The statistical analysis of the experiments carried out in the finishing train of the 2000 mill during hot rolling thin strips of low-carbon steel, allowed to identify maximum shifts of the housing screws up (+ΔS) and down (-ΔS) the stands, when the strip flatness does not change between the stands and at the mill outlet, and to determine the value ξ_i depending on the rolled piece thickness and width ratio h/B [2]:

$$\xi_i = a_0 \cdot (h / B)^{a_1} , \quad (5)$$

where $\alpha_0 = 2.95$; $\alpha_1 = 1.18$, by $0.001 \le (h/B) \le 0.03$.

It has been found that in the first stands of the finishing train there is a wide range of difference values of the relative strip profiles ξ_i, and therefore the influence (force) should be limited by an acceptable adjustment range determined by its capabilities, for example, forced bending of the working rolls:

$$[\Delta\delta S] = |\Delta Q_{max}| \cdot \frac{\Delta\delta S}{\Delta Q} . \quad (6)$$

Form and adjustment range limit ratios depend on the design of mill stands and the h/B ratio, which, when decreased, makes the flatness limit the key factor (the last mill stands).

The simulation of strip hot rolling in the continuous mill has made it possible to find out that when the profile of the active forming rolls in the two or three penultimate stands is changed, the efficiency of the thin strip profile control at the mill outlet δh_n in consideration of flatness limits is 1.1 - 1.4 times higher as compared with the last stand capabilities. When rolling thin strips (h = 1.5 - 3.0 mm), the influence efficacy of the working rolls bending in the last four or five stands is 2 - 10 times higher than those of the previous ones.

The approximation of the value ξ_i depending on the h/B ratio by the formula (6) allows to make a stable adjustment of the finishing train of the 2000 wide-strip mill on a stable rolling strips.

As the adjustment of the finishing train cannot be made perfectly due to measurement errors and various random disturbances, it is necessary to know the change range of controlled parameters, such as rolling force, where there is no strip stability loss. The study of up and down displacement of the housing screws with acceptable stability limit when rolling strips of up to 4 mm thickness has allowed determining the acceptable rolling force deviation range, where it is possible to retain strip flatness and process stability. Change in the rolling force ΔP, where strip flatness and stable process retain in conditions of NLMK 2000 mill, depending on the h/B ratio, can be approximated by the formula:

$$\Delta P = \pm 93320.7\,(h/B)^{1.08}, \text{ kN}. \quad (7)$$

Fig. 2 shows the limit ratio of metal flatness and adjustment range for rolling conditions of NLMK 2000 mill. Line 1 in Fig. 2 shows the limit change in the profile of the active roll element in the mill stands while adjusting with anti-bending devices. The control efficacy of the finished strip profile by various stands without flatness limit can be measured relative to the final stand by the formulas (3) and (7). Curve 2 in Fig. 2 illustrates variation limits $\Delta\delta S_i$, conditioned by the rolled piece flatness. In the first stands of the finishing train there is a wide range of difference values of the strip relative profiles ξ_i, therefore force constraints in the first stands (I = 1 - 3) should be

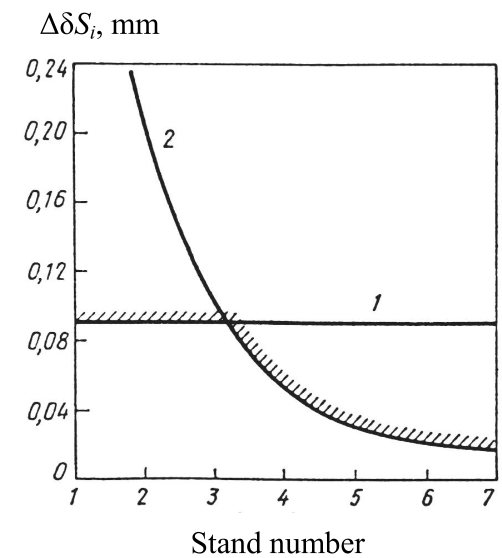

Fig. 2. Working roll active element profile limits in the finishing train $\Delta\delta S_i$: 1 - control range, 2 – flatness.

expressed not by the strip flatness, but by the acceptable control range determined by its capabilities, for example, by the forced bending of working rolls.

The introduction of the research results of the control efficiency of strip longitudinal polythickness and flatness by means of anti-bending element of working rolls in the 2000 rolling mill has resulted in the following: the actual weight of the hot-rolled coils and sheets has been reduced due to the reduction of their longitudinal polythickness; the flatness quality of hot-rolled strips and sheets has improved; the productivity of cross-cutting units has increased as the amount of unscheduled downtime has decreased.

Control of the temperature and the high-speed mode of hot strip rolling

The efficient control of the production line "slab reheating – strip hot rolling" means the control of temperature and deformation modes of metal working with the specified values H_{sl}, H_b, h and the slab width B. Metal temperature in the key points of the technological line may vary within certain limits, providing the required strip quality parameters at the mill outlet and being the most important controlled parameter which ensures effective coordination of control subsystems of certain parts of the process line.

To calculate the strip temperature at different points of the production line, a technique of describing changes in the strip cross section average (bulk) temperature of the metal, which is based on the calculation of the strip heat balance, has been developed. The technique takes into account the following:

strip heat loss due to the emission and convection into the environment, its contact with the stand working rolls, heating and evaporation of the cooling water;

strip heat gain due to the metal deformation.

In the suggested technique the metal temperature at the outlet of the rolling stand T_{out} is presented as a complex function of various rolling parameters, of which the most significant are: T_{in} - metal temperature at the inlet of the deformation zone, h_0 и h_1 - rolled piece thickness at the inlet and outlet of the deformation zone, respectively, V - rolling speed at the stand outlet, G - geometric parameters of the process equipment (stands and roller tables). Therefore:

$$T_{out} = F(T_{in}, h_0, h_1, V, G) \tag{8}$$

Given the above-stated information, it is evident that the metal temperature and reduction and rolling speed are the main controlled factors to optimize the rolling process in terms of improving technical and economic efficiency.

The developed patterns and techniques have allowed determining proper operating practices of temperature and the strip geometric parameters control.

The developed method for calculating metal temperature (5) was used to simulate the various temperature-speed conditions of strip hot rolling that can reduce production costs. Specific (per mass unit of metal products) fixed costs are inversely proportional to the performance of the metal producing units, and specific variable costs are directly proportional to the resources used per production unit.

In the production of hot-rolled strips the reduction of specified fixed costs is primarily based on the increase of the average rolling speed in the finishing train, because the productivity of the finishing group tends to be lower than the performance of the roughing train and the furnace sector. The average rolling speed in the finishing train depends on the values of the rolling charging and maximum velocities, of the mill acceleration speed and the strip length. It should be noted that the increase in the rolling speed causes the increase in the strip temperature at the outlet of the mill (rolling temperature T_{fr}). A radical means of lowering the rolling final temperature is forced cooling of metal in water between finishing stands, which gives ample opportunities of additional metal temperature control in conditions of high-speed modes that enhance the mill productivity and the quality of hot-rolled strips.

In optimizing conditions of rolling temperature and speed in the finishing train with forced cooling, the objective function can be formulated as follows:

$$I = c_1 I_1 + c_2 I_2 - c_3 I_3 = c_1 \frac{1}{L_{strip}} \int_0^{L_{strip}} \left| T_{fr}^* - T_{fr}(l) \right| dl + \\ + c_2 \frac{1}{\tau_c} \int_0^{\tau_c} G_{spec}(\tau) F d\tau - c_3 \frac{q}{\tau_c} \int_0^{\tau_c} V(\tau)\, d\tau \tag{9}$$

Here T_{fr}^* and $T_{fr}(l)$ - specified and actual rolling final temperature over the strip length l; L_{strip} - the strip length; τ_c - rolling cycle time; $G_{spec}(\tau)$ - the current value of water flow specific rate determined in the function of the required heat emission coefficient; *F* - the total area of metal cooling in spaces between the stands; q - strip linear mass; $V(\tau)$ - current value of speed rolling; c_1-c_3 - weight coefficients.

Value I_1 determines control quality, i.e. characterizes average temperature deviation from the given value per a strip length unit. Values I_2 и I_3 determine control efficiency; wherein I_2 - water flow rate per hour for forced cooling, I_3 - average finishing train productivity per hour Q. The optimization of the temperature-speed mode of the rolling with forced cooling is achieved by selecting controlling action, providing a minimum functional I with rolling final temperature limits, specific water consumption, rolling speed and the mill acceleration.

For thin strip rolling with a maximum possible acceleration and forced cooling the following dependence has been obtained [1]:

$$V_{max} = b_0 + b_1 V_{coil}, \qquad (10)$$

where V_{coil} - charging rate of the strip into the coiler; the values of coefficients b_0 and b_1 are determined for a particular mill and a strip thickness.

To determine the maximum charging rate for rolling thick strips without acceleration with forced cooling the following dependence is proposed [1]:

$$V_{\max} = \frac{T_{\text{fr}}^{*} - (k_1 h + k_2)\cdot T_{\text{f}} + k_3 h - k_4 - \alpha_{\max}\left(k_5 h - k_6\right)}{k_7 - k_8 h + k_9 \alpha_{\max}} \qquad (11)$$

T_f - the temperature at the inlet of the finishing group; h - the strip thickness at the outlet of the mill; α_{max} - experimentally determined maximum possible value of the coefficient of the strip heat loss to the cooling water; k_1-k_9 - empirical coefficients.

Dependences (10) and (11) have been used to calculate a possible increase in the 1700 rolling mill productivity in rolling with forced interstand cooling at high speeds, which is 25 - 17 % in rolling strips of 1.5 - 2.0 mm thickness; 13 - 0.5 % in rolling strips of 3.0 - 5.0 mm and 9 – 56 % in rolling strips of 6.0 - 12.0 mm.

CONCLUSIONS

The control of strip hot rolling is a challenging problem due to the interaction of various rolling parameters. The desired rheological and geometric parameters can be provided in various ways. In this regard, while developing algorithms and control systems, it is necessary, first of all, to clarify the interaction of the process variables taking into account systemic influence of control and disturbances on strip quality in consideration of technological constraints and performance.

Calculating methods which provide a choice and implementation of control modes, taking into account technological constraints, have been developed. The use of these techniques has produced original technical and technological solutions for the control of steel strip hot rolling. Examples of science-based technical solutions for the production of hot strips in the mills 2000 and 1700 have been given. Given also have been the control efficiency assessment in improving the quality of rolled products in the production of rolled steel strips in wide-strip hot rolling mills.

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