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Generalized algorithm aided design modes of rolling and its application for developing technology of pltcm 2000

The development of working patterns of rolling is very important to create and update a technology of producing steel strips. In addition, it used in estimation of a possibility of equipment for producing new dimensions of steel strip. We used the invariable method to design the pattern of rolling, which based on automatic computer-assistant engineering. With help of this method, for example, we have calculated rational total strain amount and rolling speed with maximum productivity for different kinds of steel grades on PLTCM 2000 (Picking Line Tandem Cold Mill). CR CAD software adjustment for the specification of PLTCM 2000 unit provided suitable matching of assessed speed modes at the combined unit with actual data as well as reduced errors of calculation of rolling effort to 0.78 MN. With adjusted software variants of PLCTM 2000, modes of rolling bands of various dimensional and grade gauge, as well as rational combinations of overall reduction and rolling speed of steel grades belonging to various strength groups at TCM 2000 mill stand were established.

Keywords: *Invariable method to designing the pattern of rolling, automatic computer-assistant engineering, cold roll, pickling line tandem cold mill, working patter of cold roll.*

The development of the rolling pattern is of high importance at the invention and improvement of technologies as well as estimation of facility performance for the output of new types of flat products. The process units performing simultaneously rolling and other metal treatment processes represent the major challenge for developers. One of such units is the facility combining the continuous turbulent chlorohydric acid pickling unit (PL) and 2000 continuous five-stand tandem cold-rolling mill (TCM 2000). The combined unit (PLTCM 2000) is intended for manufacture of 0.28–3.0 mm thick and 850–1850 mm wide cold-rolled bands of different grade steels and of different types (LC, HSLA, IF-HSS, BH, DP, CP, TRIP) in coils weighting up to 35 t. Starting stocks for their manufacture are 1.2–6.0 mm thick hot-rolled bands. Band speed in the pickling bathes can amount 4.7 $m \cdot s^{-1}$, maximum rolling speed is 25 $m \cdot s^{-1}$.

The combination of TCM and PL requires solving a number of tasks related to the matching the operating modes of pickling line and continuous mill. Among them is the mode selection of pickling of semi-finished hot-rolled steel and rolling providing execution of unit's operational program with prevention of cold-rolled bands faults [1]. With maximum cost-cast relationship, the mentioned tasks can be solved by combination of analysis of actual operating modes

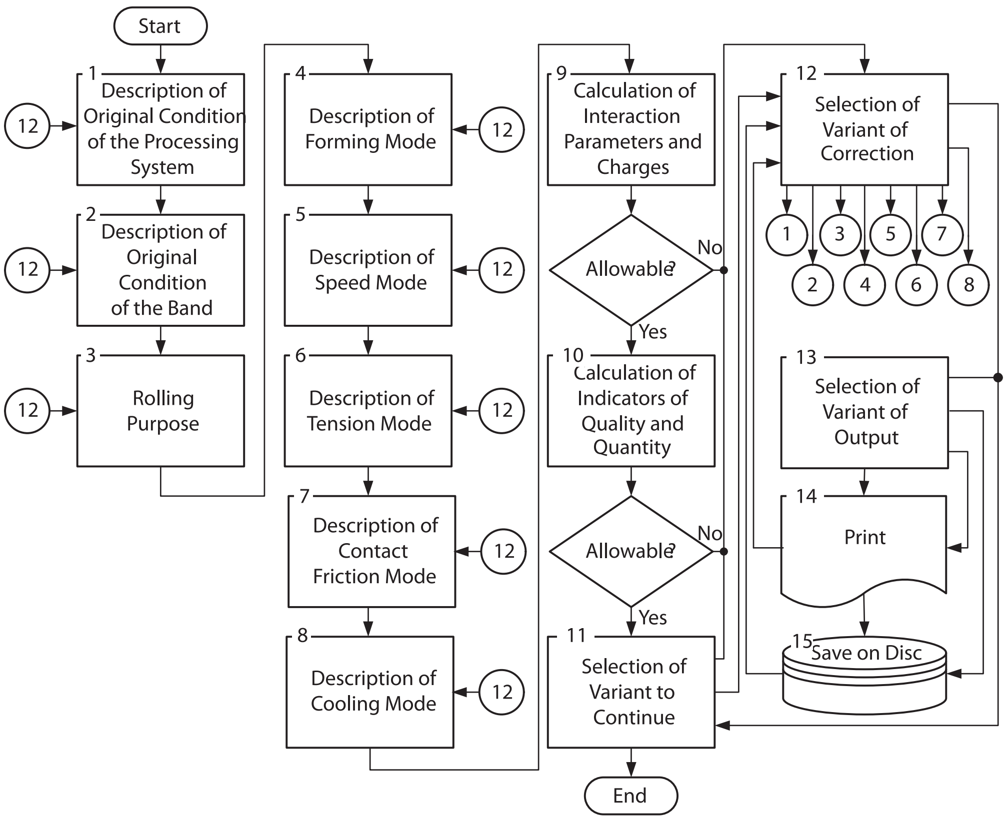

Figure 1. Generalized Algorithm of the Automated Designing Rolling Modes

of the combined unit with application of automated design engineering to find solutions of their necessary improvement.

In terms of algorithmization, the task of designing of a rolling mode may be considered invariably in relation to the type of the rolled section. The peculiarities of rolling sections of particular type are represented in numerical schemes and in variety of limitations used. On the basis of the above-mentioned concept, the invariant (generalized) algorithm (**Fig. 1**) and software structure of automated design engineering of rolling pattern have been developed [2]. Thus represented data system can be used to develop modes of rolling any sections at any rolling mill. The peculiarities of rolling sections of different type and applied equipment (machining system) are taken into consideration in the special mathematical support which can be used not only for implementation of procedures 9 and 10, but also for description of the initial approximation of the rolling modes generated at the beginning of designing by sequential execution of procedures 4–8 (**Fig. 1**). On the basis of generalized algorithm the software for automated designing cold-rolling modes, CR CAD [3], has been developed.

For the development of rolling modes of steels which deformation peculiarities have not been established yet, the forecast models of yield point of steels with random chemical composition are provided in the software. The yield point of semi-finished hot-rolled stock is calculated in function of chemical composition of steel as well as temperatures at the end of rolling (t_{ert}) and reeling (t_{ct}). The following relevant equations for the forecast of yield point are achieved with regression analyses of rolling 1640 mm bands:

$$\sigma_H = 338.1 - 460.5C^* - 4.88\frac{1-Al}{C^*} + 0.182t_{ert} - 0.149t_{ct}; \quad (1)$$

$$\sigma_H = 619.2 + 291.3C^* + 1.495\frac{1-LA^*}{C^*} - 0.323t_{ert} - 0.124t_{ct}; \quad (2)$$

$$\sigma_H = 93.38 + 967.58C^* + 43.34\frac{1-Al}{C^*} - 14.35\frac{1-LA^*}{C^*} - 0.151t_{ert} - 0.017t_{ct}; \quad (3)$$

$$\sigma_H = 658 + 343.3C^* - 254.04\frac{(1-Al)}{C^*} + 216.27\frac{(1-LA^*)}{C^*} + 0.591t_{ert} - 0.99t_{ct}. \quad (4)$$

In (1)–(4) equations $C^* = C + Mn/6 + Si/3$ is carbon equivalent value, %; $LA^* = Ti + Mo + V + Nb$ is total amount of micro-alloying elements, %. Specifications of their applications are represented in **Table 1**.

Comparison of results of approximation of curves of hardening different steel grades with the application of known dependences [4-6] shows that mechanical hardening can be represented best by the power-law relation

$$\sigma_s = C_\sigma \varepsilon^n , \quad (5)$$

which, relying on the results of the conducted study, can be presented as follows [7]:

$$\sigma_s = \left[510.2\ln(\sigma_H) - 2707.9\right]\left(100\frac{H-h}{H}\right)^n ; \quad (6)$$

$$n = 0.42 - 0.3C^2 - 0.35Si + 0.19Mn^2 - 3.73S + 33.3P - 1020.45P^2 - 5.07Ni + 54.62Ni^2 - 2.37Cu + 9.73Cu^2 - 144.14Ti^2 - 9.77Nb. \quad (7)$$

Certainty index of approximation of dependence (7) is $R^2 = 0.906$, for dependences (1)–(4) it is within the range 0.796–0.889. These R^2 values are statistically significant with confidence coefficient of 95% [8].

The procedure of calculation of coefficient of contact friction [9] has been adjusted to PLTCM 2000 conditions, on the basis of its results the ranges of variations of friction coefficient in the TCM mill stands have been established (**Table 2**). Combined with the model of precast of the yield point related to the steel chemical composition, adjustment of methods of calculation of friction coefficient enables cutting errors when calculating roll pressure from 3.5 MN to 0.78 MN.

Coherence of operation of the pickling unit and continuous mill can be achieved by selection of the unit speed mode at which band speed at the input of stand v_H equals to speed v_{PL} of the band transfer through the pickling bathes, which is determined due to the criteria of the quality scale removal. At the other side, value v_H is specified by rolling speed in the last mill stand $v_{TCM}^{(k)}$ and value of draft of hot-rolled H thick band into the cold-rolled h_k thick one. So, in the steady mode of the combined facility the following condition has to be met:

$$v_H = v_{TCM}^{(k)} \cdot h_k / H = v_{PL} . \quad (8)$$

Speed of semi-finished rolled stock $v_{TCM}^{(k)}$ must not exceed some rational value for particular deformation conditions which at first approximation can be found from the formula as per [10] with some adjustments

Table 1. Specifications of applications the equations (1)–(4)

Equation	C^*,%	$(1 - LA^*) / C^*$, %	t_{ert}, °C	t_{ct}, °C
1	0.05–0.12	8.3–18.1	860–890	500-670
2	0.13–0.6	1.5–7.5	830–890	600-680
3	0.5–0.7	1.2–1.8	840–880	600-680
4	0.2–0.5	1.5–4.1	770–860	560-650

Table 2. The friction coefficient in the stands of TCM 2000

Stand	Friction Coefficient
1	(0.050–0.120) / 0.085
2, 3, 4	(0.040–0.080) / 0.060
5	(0.038–0.255) / 0.147

$$v_{TCM}^{(k)} = k_{cp} \cdot k_{\sigma} \cdot k_{hb} \cdot v_{\max}^{(k)}, \quad (9)$$

where $v_{\max}^{(k)}$ — maximum allowable speed of rolling in the last mill stand according to its technical specifications; k_{σ} — coefficient of impact of the semi-finished rolled stock strength (assumed dependent on the yield point of the hot-rolled band σ_H in accordance with values of **Table 3**); k_{cp} — factor of assurance for process adjustment (if $k_{\sigma} \cdot k_{hb} \leq 0.9$, then $k_{cp} = 1.0$); k_{hb} — coefficient of impact of the section dimensions, which depend on band thickness and relation of its width b to length of working roll body L_{wr}:

$$k_{hb} = 0.769 \cdot h_k^{-0.3687} \cdot (b/L_{wr})^{-0.1015}; \quad (10)$$

The speed of the band travel through the L_{PL} long pickling bath can be calculated by formula

$$v_{PL} = L_{PL}/\tau_{pt}, \quad (11)$$

where τ_{pt} — period of scale removal (s) which depends on mass of scale on the band.

To determine scale mass and period of its removal the 2.0–3.6 thick samples were used which had been selected from hot-rolled bands of steel with various chemical composition (**Table 4**), having been rolled at temperature of the rolling end t_{ret} = 840–890 °C and reeling temperature t_{ct} = 530–730 °C.

For each thickness and grade of steel 9 experiments were carried out, at which parameters of the pickling solutions were varied within the following limits: acid concentration [HCl] = 44–184 g/l, iron salt concentration $[FeCl_2]$ = 45–230 g/l, temperature of solution t_{ps} = = 40–80 °C. The total number of observations amounted 81, on the basis of their results the following approximations were constructed:

$$\tau_{pt} = 2.1 \cdot 10^8 [\mathrm{HCl}]^{-2.069} [\mathrm{FeCl_2}]^{1.437} t_{ps}^{-3.757} m_{sc}^{0.727}, \ s; \quad (12)$$

$$m_{sc} = 56.35\left(\frac{t_{\text{кп}}}{1000}\right)^2 + 846.7\frac{t_{\text{см}}}{1000} - 646.5\left(\frac{t_{\text{см}}}{1000}\right)^2 - $$
$$-2.9\frac{1-LA^*}{C^*} + 0.133\left(\frac{1-LA^*}{C^*}\right)^2 - 253.83, \quad (13)$$

where m_{sc} — mass of scale on the hot-rolled band, g/m^2. For relation (12) the confidence coefficient of approximation is $R^2 = 0.988$, for relation (13) – $R^2 = 0.898$ providing degree of conformity of the predicted and actual values. These R^2 values are statistically significant with confidence coefficient of 95 % [8].

The matched speed mode of the combined pickling unit and continuous mill is selected as follows. At the given dimensions and yield period speed v_{PL} is calculated by formula (11), while rational speed $v_{TCM}^{(k)}$ in the last mill stand is established by formula (9). Then speed $v_{TCM}^{(k)}$ on the input of v_H mill corresponding to the achieved value is defined:

$$v_H = v_{TCM}^{(k)} h_k / H. \quad (14)$$

Further, the values v_H and v_{PL} are compared. If $v_{PL} > v_H$, then the speed mode of the combined unit is limited by rolling speed and, therefore, band speed in the pickling bathes should be decreased to the value

$$v_{PL} = v_{TCM}^{(k)} h_k / H. \quad (15)$$

If $v_{PL} < v_H$, then the speed mode of the combined unit is limited by band speed in the pickling bathes and rolling speed in the last continuous mill stand should be decreased to the value

$$v_{TCM}^{(k)} = v_{PL} H / h_k. \quad (16)$$

In order to establish rational combinations of the overall reduction and speed of band rolling, the steel grades specified in **Table 5** were selected. With the CR CAD software for automated designing the rolling process of the hot-rolled semi-finished stock with thickness H, from 1.8 to 6 mm, was simulated for each steel grade to establish the maximum reduction during cold-rolling at which conditions of pickling and rolling would fulfill the limit complex. Amongst others no-slip conditions of rollers, deformation metal heating up (max 220 °C), power and mechanical specifications of rolling (force, torque, capacity) and speed v_{PL} were estimated. The total calculation number amounted 120.

The calculation data showed (**Fig. 2**) that reduction up to 85% could be achieved for steel grades of the first strength group (HC180Y, 08Ю, Ст3сп- killed steel), the rational rolling speed being 16.5–17 m·s^{-1}. Bands of steel of the second strength group (HC260LA, HC300LA, HC340LA) can be rolled with overall reduction to 80 %, rational speed being 16–18.5 m·s^{-1}. The specific feature of these strength groups is that within 75–85% reduction range the matched speed mode of PLTCM 2000 unit is defined by rolling speed due to the thermal resistance of lubricating agent. At lower values of overall reduction the matched speed mode is specified by band speed in the pickling bathes. We recommend to perform rolling steels belonging to strength

Table 3. Coefficient of impact of semi-finished rolled stock on the speed of cold rolling

σ_H, MPa	k_s
Under 300	1.00
310 – 350	0.95
360 – 400	0.85
410 – 450	0.80
Over 450	0.75

Table 4. Ranges of variations in element content in the investigated steel grades

C	Si	Mn	S	P	Al	Mo	Nb	V	Ti
0.005–0.06	0.01–0.14	0.14–0.73	0.006–0.08	0.008–0.068	0.036–0.048	0.002–0.004	0.001–0.041	0.003–0.008	0.001–0.047

Table 5. Specifications of steels of various strength groups

Strength Group	Steel Grade	C^*, %	LA^*, %	t_{ret}, °C	t_{ct}, °C	$\sigma_н$, MPa
I	H180Y	0.07	0.08	830	560	306
	08Ю	0.06	0.01	850	670	288
	Ст3сп	0.27	0.01	850	630	352
II	HC260LA	0.14	0.02	830	580	330
	HC300LA	0.15	0.02	820	550	340
	HC340LA	0.22	0.04	820	570	354
III	09Г2С	0.57	0.01	810	580	451
	HX420LAD	0.60	0.06	850	580	448
	DP600	0.26	0.07	850	590	519
IV	HDT1200M	0.47	0.26	870	640	531
	DP1000	0.57	0.02	850	590	552
	HCT980X	0.67	0.20	870	630	642

group 3 (09Г2С, DP600, HX420LAD) with max 67–70% overall reduction at speed of 13–15 m·s^{-1}; rolling of steel of strength group 4 (HTD1200M, DP1000, HTC980X) – with reduction up to 58–63% at speed of 7.5–10 m·s^{-1}. At any overall reduction value of steel grades belonging to the above groups the speed of the combined unit is determined by speed of a band traveling through the pickling bathes.

Thus, the generalized algorithm of automated design engineering of rolling modes has been developed which can be transformed into software of automated design engineering for band cold-rolling modes of various application with the mathematical support. On the basis of this algorithm, the CR CAD software for automated design of band cod-rolling process modes has been developed which specifically provides the forecast of yield point and deformation hardening of steel with random chemical composition. CR CAD software adjustment to the specification of PLTCM 2000 unit provided suitable matching of assessed speed modes of the combined unit with actual data as well as reduced errors of calculation of rolling effort to 0.78 MN. With adjusted software variants of PLCTM 2000, modes for rolling bands of various dimensional and grade gauge, as well as rational combinations of overall reduction and speed of rolling of steel grades belonging to various strength groups at TCM 2000 mill stand were established.

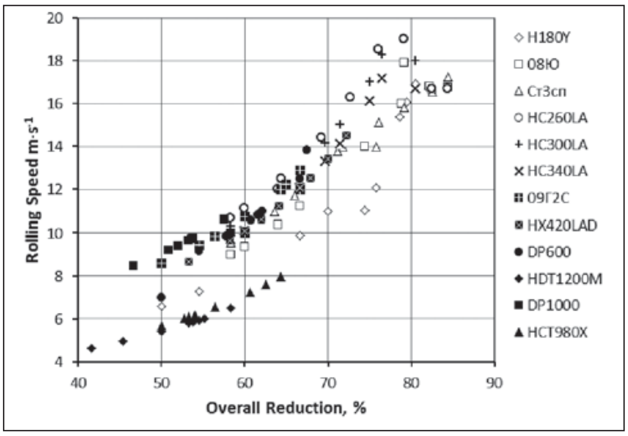

Figure 2. Rational Combination of the Overall Reduction and Rolling Speed of TCM 2000

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Optimization of long products rolling and cuttung technology based on modern it

In modern industry information technology and electronic system design, simulation, control systems, production flows, systems of control and accounting of production resources are playing a growing role. Metallurgical production isn't an exception too. There is a task in the section and long product rolling companies associated with the shipment of finishing product by gage lengths. The application of mathematical modeling based on the use of modern information technologies contributes to the efficiency of solving such problems. After the completion of implementation of such APCS the off-gauge length management at the rolling mill will be automated — optimal rolling schedules will be chosen based on the weight of the billet and wear of the rolls. The use of APCS will reduce the number of defects in production and will increase the automation level of the mill increasing the efficiency of the personnel, reducing the influence of human factor and reducing production costs. The economic effect from implementation of the system is more than 50 million rubles per year on heavy-medium section mill with production capacity of about 500 000 tons per year [1]. A promising development of APCS is not only increasing the level of automation, but also the extension of the supported range, for example, the section profiles.

Key words: *off-gage length, not custom length, off-gage balance, measuring length, cut, varying cross-sectional area of the finished product, reducing metal losses, increasing efficiency of the rolling production, variation of the roll gap, information technologies, optimization technology of the cutting, long products rolling.*

In modern industry information technologies (IT) are playing a growing role and metallurgical industry isn't exception. Electronic system design, control systems, production flows, systems of control and accounting of production resources, and automated control systems (management information system) and automated control systems of technological processes (APCS) — all of that is the norm for modern industry. For example, all of the modern continuous rolling mills are equipped with APCS that controls the speed of the mill at each stand to provide the desired tension in the stock, there are also cases where you can meet APCS that control roll gaps online.

IT spreads due to the high efficiency, automatic operation without human's intervention and a high speed of response to the changing process conditions. On the basis of the conducted researches [1], we can conclude that a promising direction in the long product rolling is the development of such an APCS, which automatically selects the optimal roll gap in the last rolling stands of the mill based on the weight of the billet and on the rolls wear to reduce defects and to improve profitability of the long product rolling production, requiring a minimal human intervention.

According to the research results we conclude [1, 2] that there is a task of the correct material cutting in front of modern bar rolling production, and the solution depends not only the volume of the finished product and yield, but also profitability. The main task of cutting is to reduce the number and length of the bars that are shorter than customers need (hereinafter off-gage length). Those bars are generated in the production process at the stage of the gage length formation.

Analysis of the production defect types during long product rolling and its percentage distribution shows that most of them were caused by the wrong cutting, i.e. off-gage length (**Fig. 1**) [2].