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SOME APPROACHES TO IMPROVE THE RESOURCE EFFICIENCY OF PRODUCTION OF FLAT ROLLED STEEL

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ABSTRACT

Possibilities of improvement of resource efficiency during the flat steel production through the use of statistical analysis of correspondence between the actual and the standardized values the characteristics of products or technological process for their production are considered. The examples of usage of this approach to define the rolling procedures that increase the yield of products with required quality are presented, as well as the examples of selecting products of the same application, but with lower resource intensity. Usage of the parameter of comparison between actual and allowable variability values (e.g. correspondence or evaluation parameter) can help to reveal technological reserves of improved quality of rolled products, as well as to prevent quality deterioration via on-line monitoring of technological procedures. Usage of correspondence parameters as differential qualimetric evaluations allows to improve objectivity and reliability of quality control as well as to approve or disprove availability of products with smaller resource intensity for replacement of products with larger resource intensity and of the same application.

1. Introduction

Increase of the yield of corresponding finished products can be considered as one of the sources of resource efficiency. Indeed, if the technological process provides manufacture of corresponding products in the required amount, then consumption of resources (including energy resources) is justified and the technological process itself can be evaluated as resource efficient one. The quality of products is forming during the technological process according to the preset procedure; however, its observance is objectively hampered by the existing fluctuations. The arising variability of the process parameters leads to variability of the quality of finished products. Thereby, it is necessary to use statistical evaluation for confirmation of meeting the requirements of the technology and products. Different aspects of this evaluation are examined rather good in the SPC (Statistical Process Control) methodology [1].

Replacement of resource intensive products by products of the same application and quality, but manufactured with significantly smaller resource intensity can be considered as another source of increase of resource efficiency. In this case it is required to use the method that can prove correspondence of quality of replacing and replaced products objectively and reliably. Taking into account variability of quality parameters, such method should be also based on the statistical approach [2].

2. Parameter (evaluation) of correspondence and principle of its application

Objective evaluation of a technological process and quality of products should reflect actual variability of their parameters in comparison with allowable variability that is preset by the requirements of standard regulations. In the case of quality regulation only by the maximal or minimal allowable values, *USL* (upper correspondence evaluation) and *LSL* (lower correspondence evaluation) can be calculated respectively as follows:

$$q_{USL} = \Delta_{USL}/3s, \quad (1)$$

$$q_{LSL} = \Delta_{LSL}/3s. \quad (2)$$

In the case of quality regulation only by the maximal and minimal allowable values, dual correspondence evaluation can be calculated as follows:

$$q_{Pk} = \min(q_{LSL}; q_{USL}). \quad (3)$$

$\Delta_{USL} = USL - \overline{x}$ and $\Delta_{LSL} = \overline{x} - LSL$ in (1) and (2) are allowable intervals of the quality parameter varying (**fig. 1**), while $3s$ is a part of its actual variability inside the allowable interval. Standard deviation s and selective average $\overline{x}$ values are used as characteristics of actual variability and dispersion center (corresponding to this actual variability). In the case of unilateral restrictions, $q_{Pk} = q_{LSL}$ and $q_{Pk} = q_{USL}$.

The correspondence parameter q_{Pk} differs from the known index of process availability P_{Pk} [1, 3] in such way, that it is used for evaluation either unit of products (if receiving of representative collections is possible), or one or several batches of the same or other kinds of products (however manufactured from steel of the same melt). At the same time, the values 1.00–1.33; 1.33–1.67 and more than 1.67 correspond to evaluations "satisfactory", "good" and "excellent" in usage of P_{Pk}.

The principle of application of the correspondence parameter for evaluation of the process state or quality of products is concluded in the following statements. The higher is q_{Pk}, the closer are the actual values of ($\overline{x}$) parameters to the middle of the interval of allowable variation, and the lower is their actual variability (s). Thereby those values of control parameters of the technological process

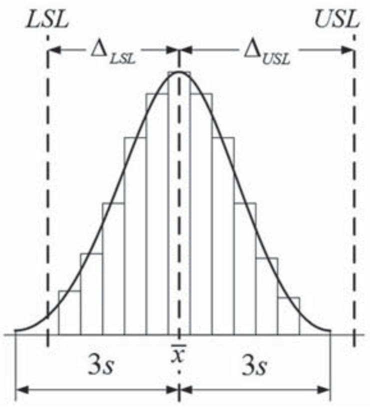


Fig. 1. On calculation of dual correspondence evaluation

and quality characteristics that provide maximal values of correspondence parameter, are considered to be the most preferential ones.

3. Increase of resource efficiency in production of rolled sheet due to reveal of technological reserves

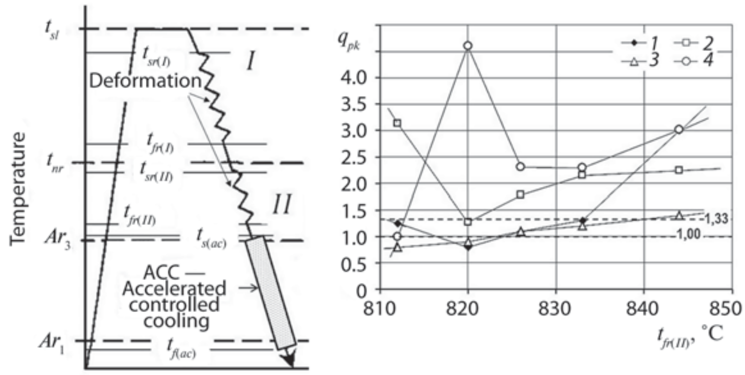
The approach to improvement of the technology due to reveal and usage of technological reserves has been suggested together with A. N. Lutsenko, O. N. Tulupov and A. B. Moller [4]. Improvement of the technological procedure in production at the heavy plate mill for large-size plates with thickness 16–20 mm can be presented as an example of usage of correspondence parameters for implementation of the above-mentioned approach. The following standard values of mechanical properties are valid for this case: yield strength $\sigma_{02} \geq 390$ MPa, tensile strength $\sigma_B =$ $= 510–660$ MPa, relative elongation $\delta \geq 20\%$, impact toughness $KCV^{-40} \geq 39$ J/m^2. The plates are manufactured via the technology of high-temperature controlled rolling (CR) with consequent accelerated cooling. In this case deformation process is separated in two stages (see **fig. 2, *a***): rolling in the area of recrystallizing austenite (stage *I*) and rolling in the area of retarded crystallization (stage *II*).

The following control parameters of the temperature conditions can be selected in correspondence the known representations, e.g. [5]: $t_{sr(I)}$ and $t_{sr(II)}$ – starting rolling temperature for the stages *I* and *II*; $t_{fr(I)}$ and $t_{fr(II)}$ – finished rolling temperature for the stages *I* и *II*; $t_{s(ac)}$ and $t_{f(ac)}$ — starting and finished temperature of accelerated cooling. In the investigated case the finished rolling temperature at the stage *II*, that is also the finished temperature of rolling process in general, has been varied from 810 to 850 °C. Analysis of the effect of $t_{fr(II)}$ on correspondence evaluations of the mechanical properties (see fig. 2, *b*) has displayed that satisfactory results ($1{,}00 < q_{Pk} < 1.33$) are observed for the case when finished rolling temperature exceeds 830 °C, while consequent elevation of $t_{fr(II)}$ finalizes in the tendency of improvement of correspondence of mechanical properties. Thereby, it is required to preset the aimed value of finished rolling temperature in the range 830–850 °C to provide satisfactory results of the process.

4. Increase of production resource-efficiency due to replacement of cold-rolled sheet metal by hot-rolled one

Evaluations presented in [6] testified that replacement of cold-rolled sheet metal by hot-rolled one can lead to economy 20 $/t, however, replacing kinds of cold-rolled steel are not specified. The author thinks [7] that usage of hot-rolled metal instead of cold-rolled sheet of general usage is the most prospective. Cold-rolled strips with thickness 1.2–3 mm, delivered according to requirements of GOST 16523 with surface finishing quality of 2 and 3 groups, make about 20% in typical dimension range of cold-rolled structural steel. In this case the part of strips with thickness 1.5–1.8 and 2–3 mm makes about 35 and 50% of this amount respectively.

As soon as choice of steel chemical composition is a priority task in production of rolled metal with preset complex of properties, characteristics of 90 batches of hot-rolled steel of current production with thickness 1.5–2 mm made of S235JR, SAE 1006, SAE 1012, SAT 1010, SS400-1, St 37-2(M) steels have been examined. Parameters of chemical composition of these batches are presented in the **table 1**. About 85–90% of hot-rolled strips are characterized by the following properties: tensile strength



a *b*

Fig. 2. Controlled parameters of temperature conditions (*a*) and influence of the finished rolling temperature on correspondence evaluations of the mechanical properties (*b*)

Table 1. **Selective parameters of chemical composition of steel grades for investigated batches of hot-rolled strip, %**

Components of chemical composition	Values		Standard deviation
	Minimal	Maximal	
C	0.090	0.190	0.023
Si	0.010	0.130	0.030
Mn	0.290	0.560	0.051
S	0.010	0.033	0.005
P	0.009	0.025	0.003
Cr	0.010	0.060	0.013
Ni	0.010	0.080	0.012
Cu	0.020	0.080	0.014
Al	0.008	0.062	0.011

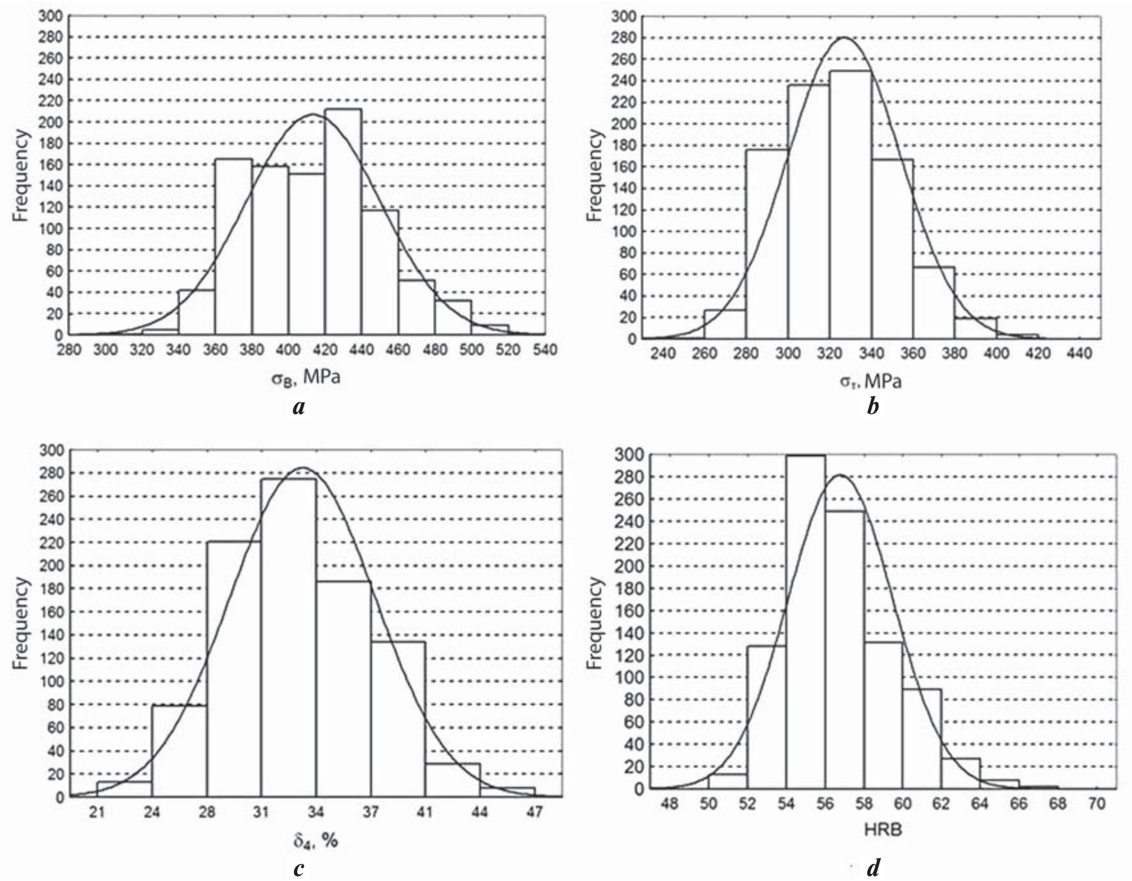


Fig. 3. Variation of tensile strength (*a*), yield strength (*b*), relative elongation (*c*) and hardness (*d*) of hot-rolled products made of investigated steels

σ_B = 360–480 MPa, yield strength σ_T = 280–380 MPa, relative elongation δ = 24–4% and hardness HRB = = 52–62 units (**fig. 3**).

Table 2 presents the example of evaluation of correspondence of hot-rolled steel of current production with the requirements of GOST 16523, meaning mechanical properties of cold-rolled metal of strength groups OK300B and OK400B. If we shall compare the average selective values $\bar{x}$ with the boundaries of regulating intervals of variation *LSL* and *USL*, we can recognize hot-rolled strips made of S235JR steel to be valid for replacement of cold-rolled sheet steel (in both cases $\bar{x}$ does not exceed outside allowance limits). Howfor ever, comparison between actual and allowable variations of tensile strength for OK300B group testifies that the center of actual variation $\bar{x}$ is located in the allowable limits, but it is shifted to the upper boundary direction. At the same time, the part of actual variation $3s = 3 \cdot 21.08 = 63.24$ MPa is larger than allowable variation by 3.4 times in relation to the upper boundary Δ_{USL}= 18.6 MPa. As a result, the excellent lower evaluation (q_{LSL} = 2.55) is accompanied by unsatisfactory upper and resulting evaluations of tensile strength ($q_{Pk} = q_{USL}$ = 0.29). At the same time, the SAE1006 steel strips are characterized by the excellent correspondence evaluation for all properties, what allows to apply the metal of these batches for deliveries instead of cold-rolled metal of the same strength groups.

Table 2. **Correspondence evaluations of mechanical properties of hot-rolled strips with thickness 2 mm made of steel S235JR (numerator) and with thickness 1,8 mm made of steel SAE 1006 (denominator) with the requirements of GOST 16523 for cold-rolled metal**

Quality parameters	Allowable variation		Actual variability		Differential evaluations		
	LSL	*USL*	$\bar{x}$	*S*	q_{LSL}	q_{USL}	q_{Pk}
Strength group OK300B							
σ_B,MPa	300	480	461,4 362,14	21,08 7,49	2,55 2,77	0,29 5,24	0,29 2,77
σ_T,MPa	215	–	353,18 295,71	18,40 7,28	2,53 3,69	–	2,53 3,69
δ_4,%	24	–	29,56 36,63	2,44 0,33	0,76 12,70	–	0,76 12,70
Strength group OK400B							
σ_B,MPa	400	680	461,4 362,14	21,08 7,49	0,97 −1,68	3,45 14,14	0,97 −1,68
σ_T,MPa	255	–	353,18 295,71	18,40 7,28	1,66 1,86	–	1,66 1,86
δ_4,%	19	–	29,56 36,63	2,44 0,33	1,44 17,72	–	1,44 17,72

Analysis of evaluations for the strength groups OK400B has displayed that strips made of SAE 1006 steel are characterized by the excellent correspondence to the regulations for yield strength and relative elongation, but they are accompanied by the negative evaluations on tensile strength, because the actual center of variation $\bar{x}$ = 362.14 MPa is less than the lower allowance boundary *LSL* = 400 MPa. At the same time, hot-rolled strips made of steel S235JR show good meeting the requirements for σ_T and δ_4, but don't satisfy to tensile strength regulations. It is caused by the fact that the part of actual variation $3s = 3 \cdot 26.5 = 79.5$ MPa exceeds the allowable variation in relation to the lower boundary $\Delta_{LSL} = 461.4 - 400 = 61.4$ MPa. As soon as the noted excess makes only 18.1 MPa, it can be concluded that S235JR steel strips will be valid for replacement of cold-rolled metal of the strength group OK400B in the case of stability rise of tensile strength.

Based on the obtained results, the method for manufacture of hot-rolled thin steel sheet has been developed for replacement of cold-rolled metal of general usage [8]. This method includes hot rolling of steel strip with preset temperature of final rolling and coiling; its feature consists of usage of steel containing 0.09–0.11% of carbon and 0.25–0.56% of manganese, with carbon equivalent $C^* = \mathrm{C} + \mathrm{Mn}/6 + \mathrm{Si}/3 = 0.12–0.18$, while the temperature of final rolling and coiling is preset based on the following correlations (°C): $t_{fr} = Ar_3 + 300C^* - 40$ and $t_{cm} = Ar_1 - (100...110)$. In this case the values of initial (Ar_3) and final (Ar_1) transformation $\gamma \to \alpha$ are calculated taking into account actual chemical composition of the concrete melt via the formulae [9]

$$Ar_3 = 913.7 - 207.13\mathrm{C} - 46.6\mathrm{Mn} + 110.54\mathrm{Cr} + 108.1\mathrm{Ni}; \quad (4)$$

$$Ar_1 = 741.7 - 7.13\mathrm{C} - 14.09\mathrm{Mn} + 16.26\mathrm{Si} + 11.54\mathrm{Cr} - 49.69\mathrm{Ni}. \quad (5)$$

Usage of (4) and (5) relationships allows to vary quickly the aimed values t_{fr} and t_{cm} for on-line compensation of natural variation of steel chemical composition and provides the required properties of hot-rolled strips intended for replacement of cold-rolled metal of general usage.

4. Stability monitoring of rolling technological procedure

SPC [1] methodology is based on monitoring of amenability of products quality and on presenting its results as control charts. However, reflected information is related to manufactured products that have been already financed. Therefore, it seems expedient to monitor the complete process parameters using control charts, in order to provide quick evaluation, choice and on-line preventing actions, i.e. for rise of the resource efficiency.

Interaction between the process control parameters and the features of requirements to products quality is one of the difficulties of such monitoring. As soon as the control charts of conventional types are divided by the groups of single-type products [10], their usage for the process monitoring will increase substantially the volume of reflected information and create visible obstacles for its understanding. The above-mentioned deficiencies can be overcome in the case of usage of correspondence parameters (1) – (3), because a lot of control charts describing the same control parameters for different kinds of products is decreased to number of controlling process parameters.

The correspondence chart (as other charts of such type) has identifiers of collections along an absciss axis and the values of correspondence parameter (calculated for the corresponding collection) – along an ordinate axis. It should be mentioned that it is allowable to use collections of different volumes. Two neighbor points on a control chart can be marked based on the results of analysis of product manufacture with essentially different requirements of regulation documents. This control chart is respectively processed at essentially different parameters of technological procedure. The control groups correspond to the boundaries of the process state areas that are accepted in SPC (1.0; 1.33; 1.67) [11]. The results of monitoring of final rolling temperature for 163 rolled coils made of different steel grades are presented as examples on the **fig. 4**. These coils have been rolled in 2000 rolling mill at Magnitogorsk Iron and Steel Works 9in the second parts of shifts).

The boundaries of allowance area are located in the range 830–900 °C, depending on steel grade, strip thickness and metal application. Several cases (e.g. fig. 4, *a*) were characterized by the excellent correspondence ($\overline{x}$ = 854 °C for allowable values 840–870 °C; standard deviation s = 2.7 °C; q_{Pk} = 1.8). For several other cases (e.g. fig. 4, *b*) the following picture has been concluded: the actual state of the technology (meaning final rolling temperature) is unsatisfactory (the center of actual variation $\overline{x}$ = 880 °C for preset temperature range t_{fr} = 860–890 °C, while standard deviation s = 4.6 °C and q_{Pk} = 0.72), nevertheless all measured values were located inside the allowance area. In general, the process effectiveness for the preset control parameter is characterized by the following data: about 30% of strips have been rolled with excellent correspondence between actual and preset temperatures ($q_{Pk} > 1.67$); about 45% of strips have good correspondence ($1.33 < q_{Pk} < 1.67$), and about 22% of strips – satisfactory correspondence ($1.00 < q_{Pk} < 1.33$) to the aimed data. Unsatisfactory correspondence ($q_{Pk} < 1.00$) is observed only for 3% of rolled coils. Such results were stipulated by timely determination of effectiveness deterioration (lowering trends on the correspondence chart) and operative correcting actions.

5. Conclusions

Evaluation of the technological process and quality of products, with taking into account actual amenability of their characteristics, can help to reveal and realize possibilities for increase of resource efficiency in rolled strip production owing to the solutions increasing yield of finished products without radical variations of technology and equipment. Usage of evaluation parameter (correspondence) can reveal technological reserves for improvement of quality of rolled products as well as to prevent quality deterioration via on-line monitoring of technological processing, because this parameter is based on compari-

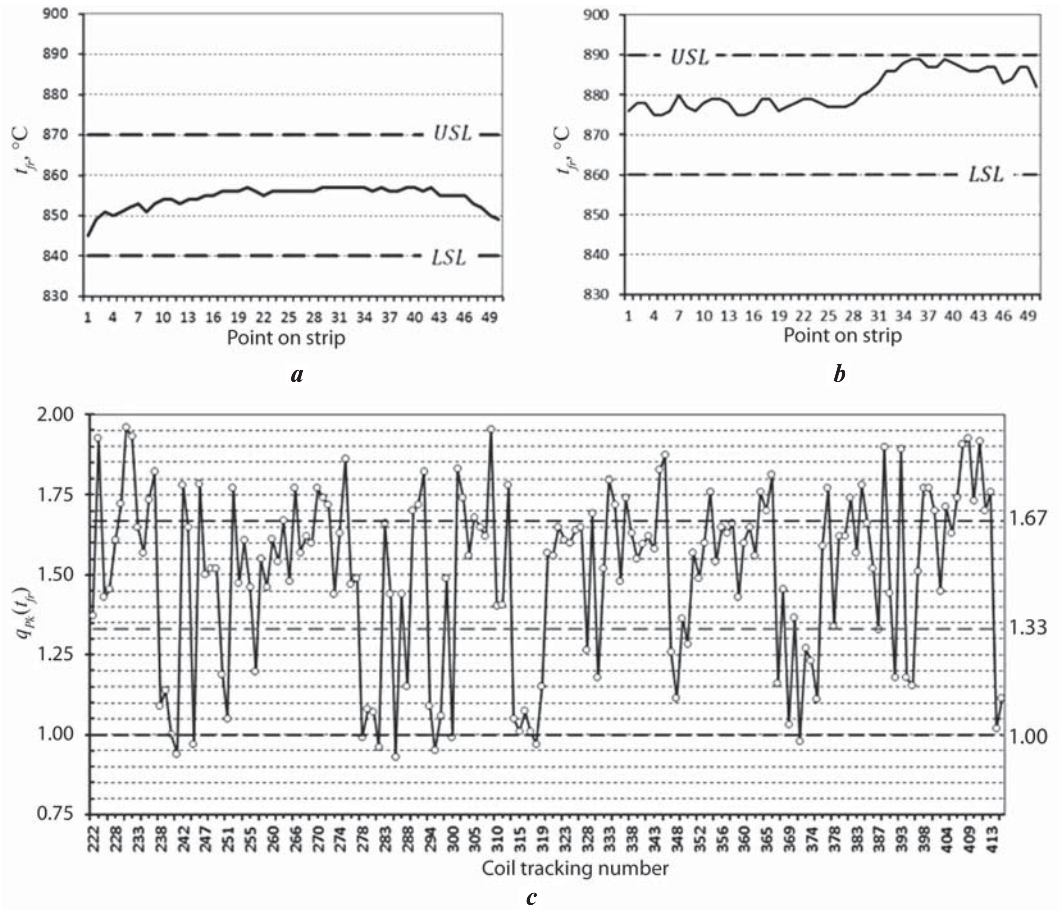


Fig. 4. Examples of excellent (*a*) and unsatisfactory (*b*) temperature distribution along strip length, as well as the correspondence chart for final rolling temperature (*c*) for the coils rolled in the 2nd part of a shift

son between amenability and allowable variation. Usage of correspondence parameter for differential qualimetric evaluations allows to improve objectivity and reliability of quality control, as well as to confirm availability of products with less resource intensity in order to replace more resource-intensive products of the same application.

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