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Influence of the Final Rolling Temperatures on the Relation between the Composition and the Mechanical Properties of K60 Pipe Steel

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Abstract—The influence of alloying and microalloying elements on the mechanical properties of pipe-steel sheet (strength category K60) depends on the temperature in low-temperature controlled rolling, on account of the polymorphous $\gamma \to \alpha$ and eutectoid transformation of austenite in the mill's finishing stand.

Keywords: pipe steel, controlled rolling, finishing temperatures, alloying, mechanical properties, phase transformations

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Sheets of steel microalloyed with strong carbide-forming elements (especially Nb and V and also Ti), produced by controlled rolling, are used in the production of pipe for gas and oil pipelines [1–8]. The performance of steel pipe may be improved by optimizing their composition and improving the thermomechanical treatment of the sheet. Classically, controlled rolling is employed, with subsequent air cooling and with accelerated cooling or quenching [4, 5, 8]. The influence of the microalloying elements on the properties of the steel may take different forms [2, 3, 6].

In analyzing the influence of the chemical composition on the properties of steel produced by controlled rolling, including analysis on the basis of mathematical models, the usual assumption is that the influence of the components remains unchanged and does not depend on the rolling parameters. At least for low-temperature controlled rolling, this approach may lead to inconsistent results and the development of incorrect recommendations regarding the optimal composition and rolling parameters.

For sheets of strength category K60 rolled on the 3000 mill at Ilich Mariupol Steel Works, we have analyzed the influence of individual components on the quality of the sheets as a function of the temperature $t_{\text{in.f}}$ of the sheet on entering the finishing stand. This temperature has the greatest influence on the mechanical properties of the steel, according to [2, 3, 6]. The content of the components in such steel is as follows: 0.07–0.13 wt % C, 0.15–0.42 wt % Si, 1.47–1.81 wt % Mn, 0.002–0.006 wt % S, 0.008–0.023 wt % P, 0.08–0.11 wt % V, 0.031–0.053 wt % Nb, 0.01–0.03 wt % Ti, 0.001–0.019 wt % Mo, 0.001–0.007 wt % Ca, and 0.020–0.058 wt % Al.

In controlled rolling of the steel, we use the following parameters: slab temperature t_{sl} = 1122–1195°C; final temperature in rough rolling $t_{\text{f.ro}}$ = 816–1022°C; initial temperature in final rolling $t_{\text{in.f}}$ = 695–753°C; final temperature in final rolling $t_{\text{f.f}}$ = 698–742°C; duration of slab heating τ_{sl} = 3.40–6.35 h. After rolling, the sheets are cooled in air (in stacks).

In the analysis, the sheets are graded in terms of the initial temperature in final rolling, with increments of 2°C, so that each group includes at least 25–30 sheets. An exception is that the sheets rolled at the lowest $t_{\text{in.f}}$ values (695–700°C) and the highest $t_{\text{in.f}}$ values (728–742°C) are combined in groups for the whole interval, since subdivision would result in too few sheets (1–3) for the development of satisfactory models. Thus, we create 14 batches of sheets, with 25–85 in each. The total number of sheets tested is 703.

Analysis of the results yields regression equations of the form

$$\begin{aligned} X = {} & A_0 + A_1[\text{C}] + A_2[\text{Mn}] + A_3[\text{Nb} + \text{V} + \text{Ti}] \\ & + A_4[\text{Si} + \text{Al}] + A_5[\text{Mo}] + A_6[\text{S}] + A_7[\text{P}] \\ & + A_8[\text{Ca}] + A_9 t_{\text{sl}} + A_{10}\tau_{\text{sl}} + A_{11} t_{\text{f.ro}} + A_{12} t_{\text{f.f}}, \end{aligned} \tag{1}$$

where A_0–A_{12} are numerical coefficients; °C is the corresponding mechanical property of the steel (σ_{u}, $\sigma_{0.2}$, δ_5, KCV_{-20}, KCU_{-60}); [C], ..., [Ca] are the contents of the components, wt %; t_{sl}, $t_{\text{f.ro}}$, $t_{\text{f.f}}$ (°C), and τ_{sl} are the process parameters defined earlier.

In the analysis, some of the steel's components are grouped together in terms of their influence on the mechanical properties: one group includes Ti, Nb, and V, which affect the dynamic and static recrystallization of austenite and the kinetics of diffusional decomposition of austenite, resulting in dispersional hardening of the steel; another includes Si and Al, which are ferrite-forming elements. In all, we obtain 70 equations: 14 for each of the five mechanical properties of the steel (σ_u, $\sigma_{0.2}$, δ_5, KCV_{-20}, KCU_{-60}). All of the equations are found to be adequate according to the Fisher test, and the variable factors are significant. In analyzing the influence of the components of 10G2FB steel as a function of $t_{\text{in.f}}$, we obtain several results that may be associated with the phase transformations in the deformation and cooling of the rolled sheet.

In Figs. 1 and 2, the coefficients for Eq. (1) are plotted. Analysis shows that, even with change in steel composition within the grade limits, the influence of the components on the mechanical properties may change as a function of the temperature in final rolling. Within the range $t_{\text{in.f}}$ = 719–724°C, change in concentration of most of the components would be expected to have no marked influence on the steel's mechanical properties.

We may assume that, with increase in carbon content, marked strengthening of the steel and increase in the relative elongation should be expected when $t_{\text{in.f}} <$ 715°C. Likewise, increase in σ_u and δ_5 would be expected when $t_{\text{in.f}} >$ 723°C (Figs. 1a–1c). However, increase in carbon content impairs the impact strength over practically the whole range of $t_{\text{in.f}}$. With decrease in $t_{\text{in.f}}$, this effect is less severe.

Increase in Mn content results in some strengthening and increase in plasticity and impact strength over a relatively broad range of $t_{\text{in.f}}$, although the properties of the wheel may be impaired when $t_{\text{in.f}} <$ 706–708°C. High concentrations of the strongly carbide-forming elements V, Nb, and Ti may be expected to strengthen the steel only at $t_{\text{in.f}} <$ 706°C (Figs. 1a and 1b). These elements may be expected to have a generally positive effect on the relative elongation and impact strength of the steel when $t_{\text{in.f}}$ = 700–725°C (Figs. 1c–1e). With increase in total Si and Al content, some strengthening of the steel may be expected, as well as increase in its impact strength, over practically the whole range of $t_{\text{in.f}}$, although the relative elongation will decrease. Under the influence of Mo, the greatest improvement in steel properties may be expected at $t_{\text{in.f}} <$ 708–710°C and $t_{\text{in.f}} >$ 725°C (Fig. 2a).

With decrease in $t_{\text{in.f}}$, the negative influence of sulfur and phosphorus on the strength and relative elongation of the steel becomes more pronounced, while their influence on the impact strength becomes less pronounced (Figs. 2b and 2c). The coefficients of the regression equations that characterize the influence of Ca are not always statistically significant. However, we may assume that increase in Ca content may improve the relative elongation and impact strength of the steel at $t_{\text{in.f}} >$ 710°C and the strength when $t_{\text{in.f}} <$ 705°C and $t_{\text{in.f}} >$ 725°C.

The influence of $t_{\text{in.f}}$ on the behavior of specific elements in the steel may be explained to some extent by intensification of the diffusional decomposition of austenite during hot plastic deformation.

For 15Г2 steel (1.3% Mn), 15Г2Ф steel (1.3% Mn, 0.08% V), and 15Г2Б steel (1.3% Mn, 0.02% Nb), which are close in composition to 10Г2ФВ steel, the temperature $t_{\text{p.t}}$ at which polymorphic $\gamma \rightarrow \alpha$ transformation begins increases significantly with decrease in rolling temperature from 1300 to 750°C, according to [1]. For example, decrease in rolling temperature from 1300 to 850°C increases $t_{\text{p.t}}$ from 725 to 820°C for 15Г2 steel; from 763 to 820°C for 15G2F steel; and from 705 to 800°C for 15Г2ФБ steel. At lower rolling temperatures (800 and 750°C), the $t_{\text{p.t}}$ value on the graph corresponds to the same rolling temperature. That indicates that the polymorphic transformation begins in the course of deformation.

Note that, in the roughing stand of the rolling mill, the steel undergoes intense hot plastic deformation, which may stimulate polymorphic transformation even on cooling before the finishing stand. Deformation at low temperatures accelerates the diffusional transformation of the austenite even more effectively.

In this context, analysis of the final temperature $t_{\text{f.f}}$ of final rolling and $\Delta t = t_{\text{in.f}} - t_{\text{f.f}}$ as a function of $t_{\text{in.f}}$ is of interest (Fig. 3). The mean values of these temperatures are obtained from the monitoring of 20–40 steel sheets at each point, except for rolling with $t_{\text{in.f}} <$ 700°C and $t_{\text{in.f}} >$ 735°C, when 3–5 sheets are considered at each point.

Many factors affect $t_{\text{f.f}}$; some act in opposite directions. Increase in $t_{\text{f.f}}$ and corresponding decrease in Δt will be facilitated by the thermal effects due to polymorphic transformation $\gamma \rightarrow \alpha$ in the deformation of subeutectic steel and subsequent conversion of the residual austenite to pearlite, plastic deformation, and perhaps the deposition of excess phase phases (carbides of V and Nb and cementite) from the supersaturated solid solution.

Decrease in $t_{\text{f.f}}$ and increase in Δt will be facilitated by natural cooling of the sheet in the intervals between passes and by contact with the mill rollers (the decrease in sheet temperature may be assumed practically constant in a fixed rolling system) and also by the development of recrystallization in austenite and ferrite, which requires additional energy.

On curves of $t_{\text{f.f}}$ and $\Delta t = t_{\text{in.f}} - t_{\text{f.f}}$ as a function of $t_{\text{in.f}}$ (Fig. 3), we note several sections.

(1) When $t_{\text{in.f}}$ is in the range from 750–755°C to 735–737°C, we note marked increase in $t_{\text{f.f}}$ (Fig. 3a)

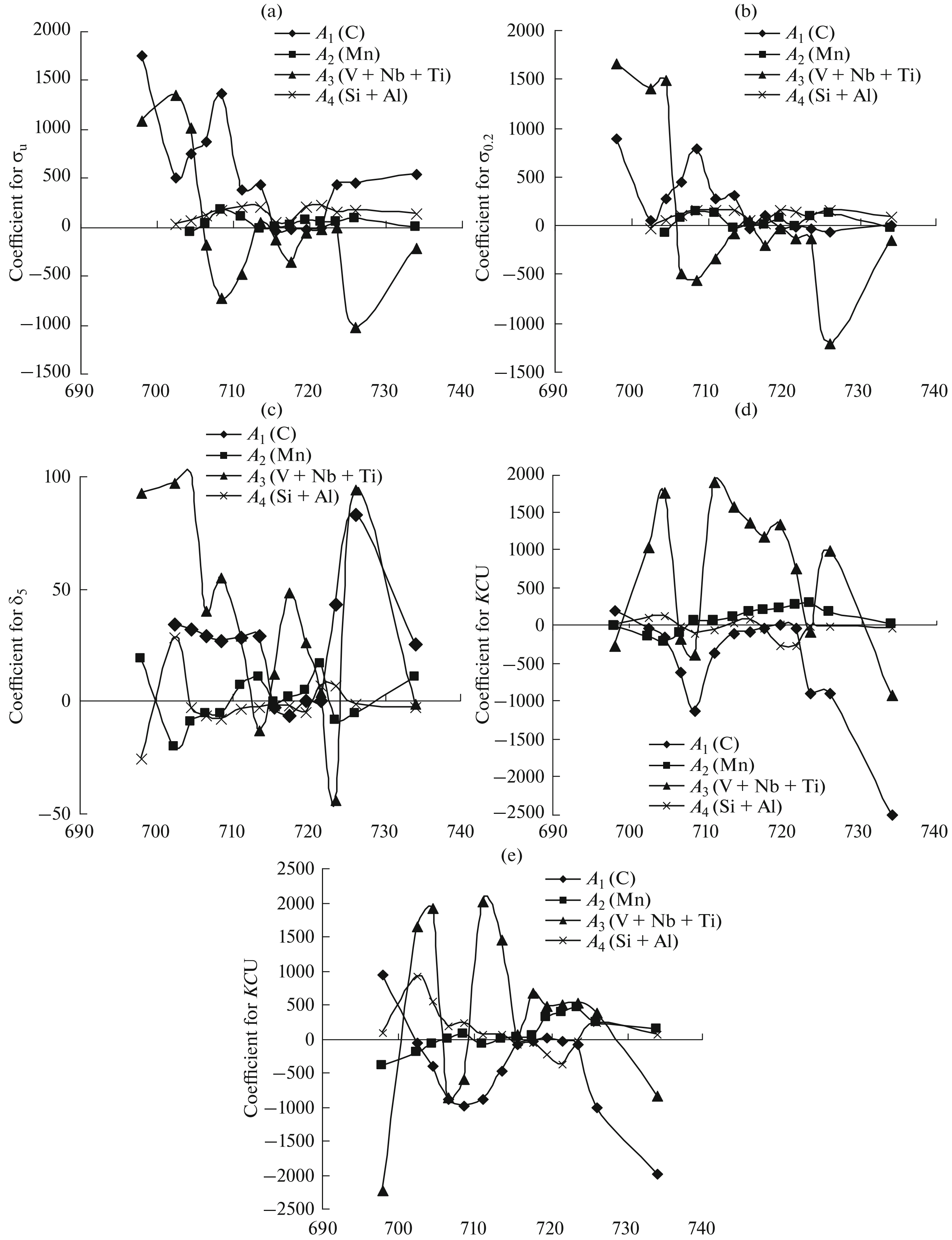

Fig. 1. Plots of the coefficients A_1–A_4 from Eq. (1) characterizing the influence of C, Mn, V + Nb + Ti, and Si + Al on the mechanical properties of 10Г2ФБ steel—σ_u (a), $\sigma_{0.2}$ (b), δ_5 (c), KCV_{-20} (d), and KCU_{-60} (e)—as a function of $t_{in.f}$ (°C).

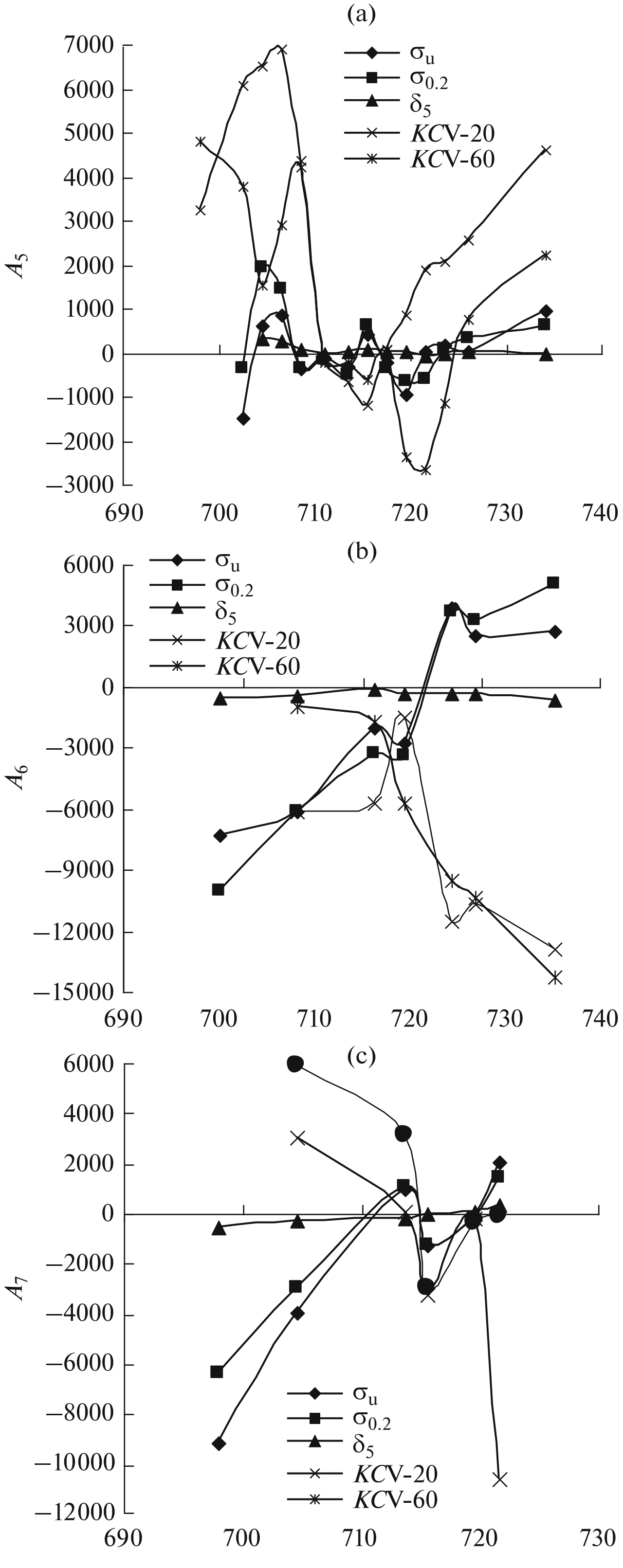

Fig. 2. Plots of the coefficients A_5–A_7 from Eq. (1) characterizing the influence of Mo (a), S (b), and P (c) on the mechanical properties of 10G2FB steel.as a function of $t_{\text{in.f}}$ (°C).

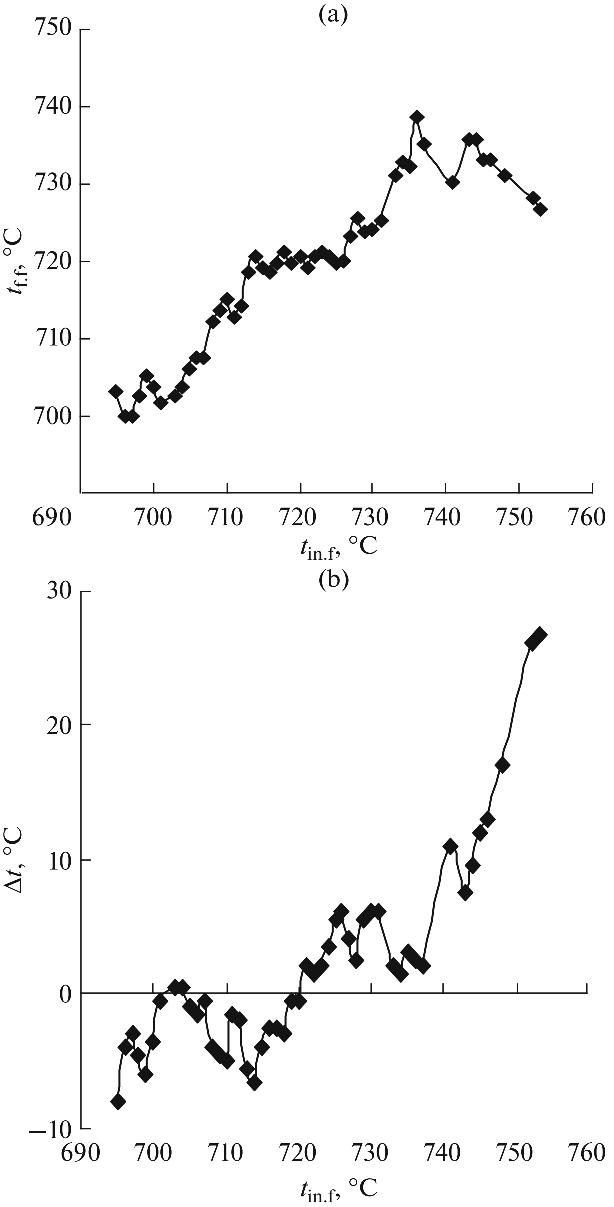

Fig. 3. Dependence of $t_{\text{f.f}}$ (a) and $\Delta t = t_{\text{in.f}} - t_{\text{f.f}}$ (b) on $t_{\text{in.f}}$.

and decrease in Δt (Fig. 3b) with decrease in $t_{\text{in.f}}$. In this section, $t_{\text{in.f}}$ remains higher than $t_{\text{f.f}}$, The increase in $t_{\text{f.f}}$ may be mainly attributed to the thermal effect of the polymorphic transformation $\gamma \rightarrow \alpha$ in final rolling. The decrease in Δt is obviously associated with decrease in the thermal effect of the polymorphic transformation as a result of decrease in the proportion of austenite undergoing polymorphic transformation to ferrite in final rolling, since much of the austenite has already undergone polymorphic transformation in cooling before final rolling. The decrease in Δt with decrease in $t_{\text{in.f}}$ in this section may perhaps be facilitated by the development of dynamic (in the course of deformation) and static (in the intervals between stages of deformation) recrystallization, with accompanying energy absorption, in both the decomposing austenite and the ferrite formed.

(2) When $t_{in.f}$ is in the range from 734–735°C to 725–726°C, we note relatively intense decrease in $t_{f.f}$ (Fig. 3a) and irregular increase in Δt (Fig. 3b) with decrease in $t_{in.f}$. This may be due primarily to structural and substructural changes in the deformed ferrite formed mainly on cooling.

(3) When $t_{in.f}$ is in the range from 725–726°C to 713–714°C, we note practically constant $t_{f.f}$ (720 ± 1–1.5°C; Fig. 3a), but marked decrease in Δt with decrease in $t_{in.f}$. When $t_{in.f} < 720°C$ (Fig. 3b), Δt is negative. This may be explained by the eutectoidal (pearlitic) transformation of austenite during final rolling. Obviously, the thermal effect of pearlitic transformation will be greater if it begins earlier in the course of final rolling.

(4) When $t_{in.f} <$ 712–713°C, $t_{f.f}$ gradually declines with decrease in $t_{in.f}$ (Fig. 3a). We must distinguish between two subranges here.

(4.1) When $t_{in.f}$ is in the range from 712–713°C to 703–704°C, we note gradual nonuniform decrease in Δt, which switches from negative values to small positive values at $t_{in.f} =$ 703–704°C (Fig. 3b).

(4.2) When $t_{in.f} <$ 703–704°C, Δt again begins to increase and becomes negative.

It is possible that, in the fourth section, final rolling occurs after the end of pearlitic transformation—in other words, in the two-phase ferrite–cementite region. The final thermal effect and correspondingly Δt will be determined by the following factors:

(1) the development of dynamic polygonization and recrystallization in the ferrite, leading to decrease in $t_{f.f}$ and hence increase in Δt;

(2) increase in the resistance to plastic deformation of steel with ferrite–pearlite structure, resulting in additional heating of the sheet and increase in Δt (this effect increases with decrease in $t_{in.f}$ and may perhaps be the most active in this temperature range);

(3) additional deposition of excess carbide (carbonitride) phases—in particular vanadium carbides—from the deformed ferrite, especially at $t_{in.f} < 700°C$, with consequent increase in Δt.

Analysis of the behavior of $t_{f.f}$ and Δt in relation to the coefficients in Eq. (1) for the different components of the steel (Figs. 1–3) shows that, in most cases, the temperature ranges characterized by different behavior of the coefficients match those corresponding to the rolling temperature.

With change in carbon content in the steel, its properties are practically unchanged when $t_{in.f}$ corresponds to the third section of Fig. 3, characterized by eutectoid transformation in the course of deformation. In the fourth section, we may expect positive influence of carbon on the steel strength—obviously on account of the intensification of vanadium-carbide deposition and the possible development of dynamic polygonization and recrystallization—but mainly its negative influence on the plasticity and ductility of the steel. With final rolling in the two-phase austenite–ferrite region (in the first and second sections), increase in the carbon content may increase σ_u and δ_5 but will decrease the impact strength.

Increase in the Mn content improves the steel strength when $t_{in.f} =$ 706–711°C (in the third and fourth sections). Increase in δ_5 with increase in Mn content may be expected in the first and third sections. The influence of Mn on the impact strength is positive when $t_{in.f} > 709°C$.

Increase in the content of Ti + Nb + V, which are strongly carbide-forming elements, improves the strength only in the fourth section. In the fourth and second sections, positive influence of those elements on δ_5 may be expected. Increase in the content of Ti + Nb + V will increase the impact strength in the third section and also in the portion of the fourth section where $t_{in.f} =$ 703–705°C. At other $t_{in.f}$ values, increase in the content of Ti + Nb + V is undesirable.

As already noted, increase in the Si + Al content should improve the steel strength and increase δ_5 at practically all values of $t_{in.f}$. However, these elements impair the impact strength in the third section, whereas they improve the impact strength in the fourth section.

Molybdenum impairs all the properties of the steel within the third section, but mainly improves δ_5, KCV_{-20}, and KCU_{-60} in the first, second, and fourth sections. However, improvement in the steel strength may only be expected in the first and second sections and when $t_{in.f} =$ 704–707°C in the fourth section.

The results indicate that the influence of the other statistically significant parameters in Eq. (1) may also depend on $t_{in.f}$. Increase in slab temperature t_{sl} may improve the steel strength in the first section ($A_9 = 0.703$ for σ_u, $A_9 = 0.78$ for $\sigma_{0.2}$), in the third section ($A_9 =$ 0.01–0.57 for σ_u, $A_9 =$ 0.01–0.43 for $\sigma_{0.2}$), and in the fourth section ($A_9 = 0.01$ for σ_u).

Increase in the slab heating time τ_{sl} improves the steel strength ($A_{10} =$ 4.95–10.90 for σ_u and 3.71–11.03 for $\sigma_{0.2}$) but impairs δ_5 (A_{10} is between –0.14 and –1.44) and the impact strength (A_{10} is between 6.6 and –36.9 for KCV_{-20}, and between –0.54 and –36.2 for KCU_{-60}), regardless of $t_{in.f}$.

Increase in the final temperature $t_{f.ro}$ of rough rolling may improve the steel strength in sections 2–4 ($A_{11} =$ 0.07–0.6 for σ_u and 0.1–0.53 for $\sigma_{0.2}$), but has practically no influence in the first section. Increase in $t_{f.ro}$ improves δ_5 for all $t_{in.f}$. Increase in the steel's impact strength with increase in $t_{f.ro}$ may only be expected in the first and second sections: $A_{11} = 0.50$ to

0.55 for both KCV_{-20} and KCU_{-60}. The impact strength will decline with increase in $t_{f.ro}$ in the fourth section (A_{11} varies from –0.042 to –0.49 for KCV_{-20}, and from –0.15 to 0.40 for KCU_{-60}).

CONCLUSIONS

(1) In low-temperature controlled rolling, the influence of alloying elements on the mechanical properties of steel will change as phase transformations develop in the course of final rolling.

(2) If the initial temperature in final rolling $t_{in.f}$ is no lower than 735°C, the development of polymorphic transformation $\gamma \rightarrow \alpha$ in final rolling increases the final temperature. In deformation with $t_{in.f}$ between 725 and 714°C or with cooling in this region, the development of eutectoid transformation stabilizes the final rolling temperature at 719–721°C.

(3) In final rolling at temperatures where pearlitic transformation is possible, variation in the content of C, Mn, and the strongly carbide-forming elements V, Nb, and Ti within the grade specifications has little influence on the steel's properties.

(4) For final rolling at temperatures where polymorphic transformation $\gamma \rightarrow \alpha$ is possible, the steel strength may be expected to improve with increase in the content of C, Mn, Si, Al, and Mo and to decline with increase in the content of the strongly carbide-forming elements Nb, V, and Ti. In this range of $t_{in.f}$, improvement in plasticity and impact strength of the steel may be expected with increase in the content of Mn and Mo, but decrease in those properties may be expected with increase in the content of Nb, V, Ti, Si, Al, and C.

(5) At the lowest $t_{in.f}$ values, corresponding to deformation in the ferrite–cementite region, improvement in steel strength and impact strength may be expected with increase in the content of C, Mn, Mo, and the strongly carbide-forming elements Nb, V, and Ti. Increase in plasticity and impact strength may be expected with increase in the content of Si and Al.

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