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MAIN STRUCTURAL FACTORS OF STRENGTHENING OF LOW-CARBON LOW-ALLOY PIPE STEELS AFTER CONTROLLED ROLLING

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The mechanical properties of a large group of commercial heats of three grades of pipe steel (17G1S-U, 10G2FB, and 12G2SB) are studied after controlled rolling. The interrelation of alloying, structure, and mechanical properties of the steels subjected to controlled rolling under the conditions of the Magnitogorsk Iron and Steel Works is studied, and the main structural factors responsible for strengthening of low-alloy steels are determined.

INTRODUCTION

A relevant direction for raising the competitiveness of metallurgical enterprises is the production of steels with a specified level of properties. However, it is known that the structure and mechanical properties differ substantially from heat to heat even for metals with simple chemical compositions like low-carbon steel of type 17G1S [1, 2].

The strict requirements on materials for delivery pipes dictate the necessity for producing steels with elevated strength. In addition to low-carbon steels, frequent objects of metallurgical production and thermomechanical treatment are low-carbon low-alloy steels. Their alloying system includes elevated contents of niobium and vanadium with simultaneous limitation of the carbon content [3 – 5]; additional alloying elements are usually molybdenum and boron [6 – 8]. When the content of alloying elements in these steels is higher than in the low-carbon group, the uncertainty about ensuring the required combination of properties increases. Specifically, experience in the production of steels 10G2FB and 12G2SB shows that their chemical composition varies with respect to several chemical elements and this determines the special features of their structure [9].

In addition to the chemical composition the efficiency of strengthening of pipe steels depends considerably on the mode of the thermomechanical treatment, i.e., the temperature, the degree, number, and rate of the deformation operations, and the cooling rate. Depending on the process parameters used at the producer plant the steels have various combinations of mechanical, process, and operating properties [10].

The aim of the present work was to study the most significant structural factors affecting the mechanical properties of pipe steels after controlled rolling and to use this knowledge for estimating the prospects of the use of low-carbon low-alloy steels under the conditions of production at the Magnitogorsk Iron and Steel Works (MMK).

METHODS OF STUDY

We studied 32 commercial heats of steels 17G1S-U, 10G2FB, and 12G2SB. The range of the alloying elements for each of the steels is presented in Table 1. The preforms were subjected to controlled rolling into sheets with a thickness of 9 – 16 mm. The actual parameters of rolled products obtained at the MMK and the specified requirements on the thermomechanical treatment of the steels in question are presented in [9]. The mechanical properties of the steels were determined by testing them by uniaxial tension at room temperature. The impact toughness was evaluated from the results of impact tests of specimens with a *V*-notch at 0 and – 40°C. The mechanical properties were analyzed using standard statistical methods of data grouping and regression analysis.

RESULTS

The set of mechanical properties of the steels was characterized by a combination of strength, ductility, and impact toughness. Figure 1 presents the relation between the yield

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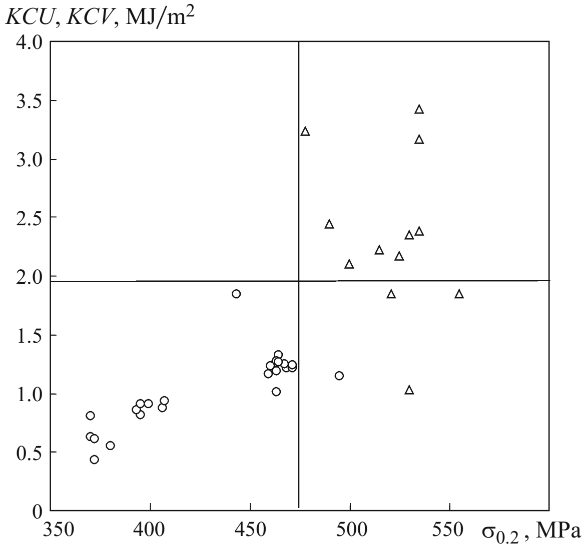

Fig. 1. Impact toughness [○) KCV^0, △) KCV^{-40}] as a function of the yield strength of the studied steels: ○) (0.10 – 0.18)% C; Mo — not regulated; △) (0.04 – 0.07)% C, (0.003 – 0.205)% Mo.

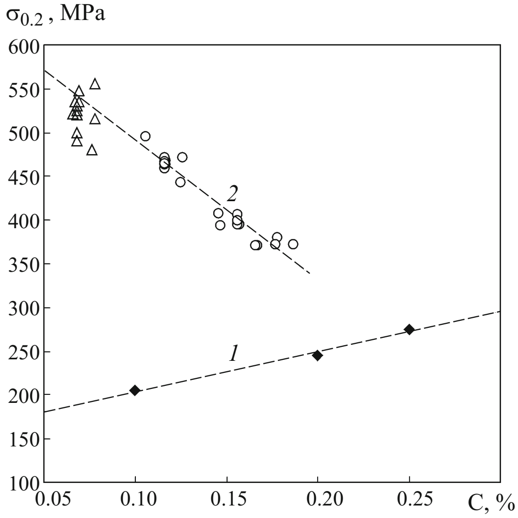

Fig. 2. Yield strength of the steels as a function of the carbon content: *1*) low-carbon low-alloy steels St10, St15, St25 [11]; *2*) low-carbon alloy steels with (○) (0.10 – 018)% C, Mo — not regulated; (△) (0.04 – 0.07)% C, (0.003 – 0.205)% Mo.

strength and the impact toughness. The yield strength was determined for all the steels under the same conditions at room temperature. The impact toughness of specimens with a sharp notch was measured at two temperatures, i.e., 0 and – 40°C. The steels containing from 0.10 to 0.18% C were tested at zero temperature; their impact toughness is marked by "○" on the diagram. For the steels with carbon content limited to 0.04 – 0.075, which were additionally alloyed with molybdenum (0.003 – 0.205%), the impact toughness was determined at a temperature of – 40°C (symbols "△" on the diagram).

TABLE 1. Chemical Composition of Studied Steels

Chemical element	Content of elements, wt.%, in steels		
	17G1S-U	10G2FB	12G2SB
C	0.18 – 0.10	0.07 – 0.04	0.06
Si	0.48 – 0.22	0.36 – 0.22	0.36 – 0.26
Mn	1.45 – 1.19	1.69 – 1.50	1.59 – 1.56
S	0.008 – 0.005	0.005 – 0.003	0.005 – 0.004
P	0.020 – 0.007	0.011 – 0.005	0.011 – 0.006
Nb	0.042 – 0.002	0.071 – 0.065	0.071 – 0.066
V	0.058 – 0.010	0.063 – 0.034	0.059 – 0.049
Ti	0.004 – 0.002	0.02 – 0.01	0.02 – 0.01
Cr	0.04 – 0.01	0.06 – 0.02	0.02
Ni	0.04 – 0.02	0.06 – 0.01	0.02
Mo	–	0.205 – 0.004	0.200 – 0.003
B	–	0.0004 – 0.0003	0.0004
Sn	–	0.003 – 0.002	0.0004

Note. The content of Al in all the steels is 0.03 – 0.04%; the content of N is 0.006 – 0.008%.

It can be seen that the experimental points on the diagram are distributed nonuniformly; when the coordinate field is divided into four equal-size squares, the majority of the experimental points is concentrated in two of them. Moreover, it can be seen that the steels with different alloying systems primarily fall onto the same square.

The points belonging to the low-carbon steel marked with symbol "○" are grouped in the left bottom square and hence the steels with elevated carbon content have the lowest values of the yield strength and of the impact toughness. This circumstance is not trivial, because in low-carbon plain steels with elevated carbon content the yield strength increases (curve *1* in Fig. 2). For steel 17G1S-U, on the contrary, the yield strength and the carbon content obey a quite obvious inverse relation (curve *2* in Fig. 2), which is connected with successive growth in the amount of carbide-forming elements in the chemical composition [9]. This can be used for predicting the mechanical properties of hardened steels in the stage of metallurgical production. The reliability of the prediction estimated in terms of the approximation factor is 94%.

Another feature of steels of type 17G1S-U (see symbols "○" in Fig. 10) is a statistically significant direct proportional relation between the characteristics discussed; the coefficient of linear correlation is 80%. This allows us to infer that the factors most substantially affecting the level of mechanical properties of steels of this group are the same in both tensile and impact tests.

For the steels with reduced carbon content all the points marked by "△" in Fig. 1 are located in the right half of the coordinate field; over 70% of their total number are concentrated in the higher right square and only 20% in the lower right one. Such location of experimental points on the dia-

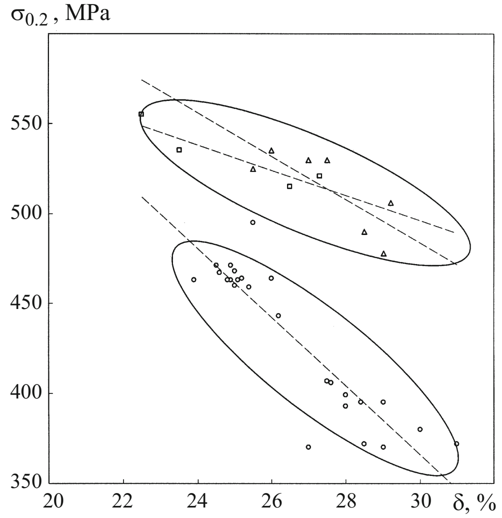

Fig. 3. Relation between the yield strength and the elongation of the studied steels: ○) (0.10 – 018)% C, Mo — not regulated ($y = -19.1x + 938.3$; $R^2 = 0.8$); △) (0.04 – 0.07)% C, (0.003 – 0.004)% Mo ($y = -12.1x + 846.1$; $R^2 = 0.6$); □) (0.06 – 0.07)% C, (0.100 – 0.205)% Mo ($y = -7.0x + 707.2$; $R^2 = 0.8$).

gram indicates that the steels with reduced carbon content additionally alloyed with molybdenum and bearing elevated contents of V, Ti, and Nb are more advantageous with respect to the yield strength and in most cases with respect to the impact toughness too. It should be noted that the impact tests for this group were performed at a temperature 40°C lower than for the first group. With allowance for the temperature dependence of the impact toughness, we can expect that if we compare the values of impact toughness obtained under equal conditions, the difference will be more noticeable.

For steels with reduced content of carbon (symbols "△"), correlation between the values of yield strength and impact toughness does not exist, i.e., the factors determining the resistance of the steels to applied load are sensitive to the loading rate. In the given case the fact that the impact toughness is more dependent on the variation of the structure than the properties under static stretching is confirmed [11]. Thus, for steels of this group it is especially important to study the conditions required for ensuring a high level of impact toughness.

Figure 3 presents the relation between the yield strength of the steels and the elongation. These data reflect the general tendency of reduction of ductility upon strengthening of the material. In addition, the entire set of experimental points on the correlation field of the diagram is grouped into two regions belonging to steels with different alloying. They differ substantially in the strength-to-ductility proportion. At equal elongation ($\delta = \sim 29\%$) the yield strength of the steels of the second group is considerably higher ($\sigma_{0.2} = 475 - 490$ MPa against $372 - 392$ MPa); at close values of the yield strength ($\sigma_{0.2} = 455 - 490$ MPa) they are characterized by higher values of the elongation (29% against 25%). This advantage does not exhaust the difference between the two groups of steel.

The whole of the set of experimental data obeys one type of functional relation between the studied characteristics $\sigma_{0.2}\,(Y)$ and $\delta(X)$, i.e.,

$$Y = -KX + B.$$

However, it can be seen from Fig. 3 that the slope of the line differs for the steels of different groups.

The possibilities of regression analysis allow us to determine the difference in the quantitative parameters of the relation. For low-carbon steels of type 17G1S-U (symbols "○" in Fig. 3) the coefficient of linear correlation is equal to 90% and the regression equation has the form

$$\sigma_{0.2} = -19.1\delta + 938.3; \quad R^2 = 0.81.$$

A regression coefficient equal to – 19.1 indicates that when the elongation increases by 1%, the yield strength of the steels of this group decreases by 19.1 MPa. Parameter R^2 equal to 0.81 shows that such relation between the mentioned characteristics is implemented accurate to 81%, i.e., the given regression equation describes the relation adequately enough.

For low-carbon steels of type 10G2FB and 12G2SB (symbols "△"), the equation transforms to

$$\sigma_{0.2} = -8.4\delta + 744.1; \quad R^2 = 0.7.$$

The decrease in the regression coefficient to – 8.4 reflects the fact that even 1% growth in the elongation is accompanied by a decrease in the yield strength by only 8.4 MPa, which is twice slower than in the steels of the first group. The correlation coefficient between the characteristics in question is equal to 84% and characterizes the relation as a quite close one. Since the volume of the studied steels was limited (11 heats), lest us estimate the significance of the correlation coefficient by Student's test. The design value of the Student criterion $t_d = \dfrac{0.84\sqrt{11-2}}{\sqrt{1-0.84^2}} = 4.58$, which exceeds the tabulated one equal to 3.25 at a significance level of 1% [12]. Consequently, we can be quite confident (with probability of 99%) that in other heats of these steels the relation between the yield strength and the elongation should behave similarly.

If we divide this group of steels in accordance with the content of molybdenum in the chemical composition, we will see that as the amount of molybdenum in their chemical composition is increased from 0.003 – 0.004 to 0.100 – 0.205%, the regression coefficient decreases from 12.1 to 7.0 MPa/%. Consequently, when the content of molybdenum increases, the alloys exhibit a tendency for improvement of the strength-to-ductility proportion. A more detailed study for a great number of heats should give a still more accurate picture of the effect of molybdenum.

DISCUSSION

The main requirements on the mechanical properties of pipe steels are high yield strength and low temperature of the ductile-to-brittle transition. The alloying additives and the structural parameters, which ensure strengthening, commonly cause growth in the temperature of embrittlement. When developing the chemical composition and the process of production of a steel, it is necessary to optimize the combination of mechanical properties due to minimum growth in the cold-shortness threshold per unit growth in the strength. Let us see how successfully this principle has been implemented. For this purpose we will use the results of [9], where the chemical composition and the structure of the steels in question have been studied in detail.

It follows from the experimental data presented in Fig. 1 that the maximum difference in the yield strength $\Delta\sigma_{0.2}$ of steels 10G2FB, 12G2SB, and 17G1S-U attains 180 MPa.

This quantity is composed of several components. Growth in the yield strength is associated with the additive action of the following factors [13]: the solid-solution strengthening of ferrite $\Delta\sigma_{\mathrm{s.s}}$, the strengthening due to pearlite $\Delta\sigma_{\mathrm{p}}$, the dislocation strengthening $\Delta\sigma_{\mathrm{d}}$, and the strengthening due to refinement of grains $\Delta\sigma_{\mathrm{g}}$ and due to segregation of fine particles $\Delta\sigma_{\mathrm{f.p}}$, i.e.,

$$\Delta\sigma_{0.2} = \Delta\sigma_{\mathrm{s.s}} + \Delta\sigma_{\mathrm{p}} + \Delta\sigma_{\mathrm{g}} + \Delta\sigma_{\mathrm{d}} + \Delta\sigma_{\mathrm{f.p}}.$$

Being an interstitial element carbon has the highest significance for the solid-solution strengthening of ferrite. Its content in steels 10G2FB and 12G2SB is about 0.1% less than in steel 17G1S-U. It can be seen from the example of plain low-carbon steel (curve *1* in Fig. 2) that this decreases the yield strength by 40 MPa. Increase in the content of carbide-forming elements Nb, V, and Ti, in the chemical composition of steels 10G2FB and 12G2SB does not affect the state of the solid solution of ferrite, because these elements are bonded into chemical compounds. Consequently, $\Delta\sigma_{\mathrm{s.s}} = -40$ MPa.

In our previous work [9] we have shown that the volume fraction of pearlite in the structure varies from 15 – 23% for steel 17G1S-U to 3 – 5% for steels 10G2FB and 12G2SB. In the low-carbon steels pearlite does not play the role of a strong strengthener. We assume that $\Delta\sigma_{\mathrm{p}} = 0$.

The study performed in [9] has shown that ferrite grains in steels 10G2FB and 12G2SB can be refined substantially as compared to steel 17G1-U. This is obvious from Fig. 4. The strengthening due to this factor can be allowed for by using the formula for the yield strength of low-carbon steels [14], i.e.,

$$\sigma_{0.2} = 15.4\{3.5 + 2.1[\mathrm{Mn}] + 5.4[\mathrm{Si}] + 23[\mathrm{N}_f] + 1.13d^{-1/2}\},$$

where N_f is the content of free nitrogen, [Mn] and [Si] are the contents of manganese and silicon, and *d* is the grain size of polygonal ferrite.

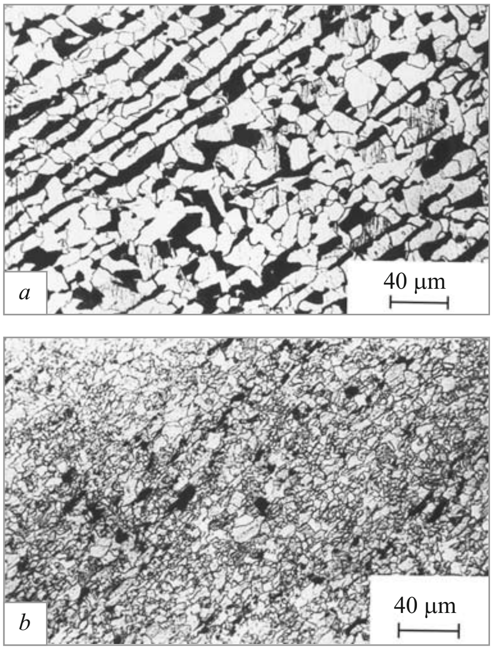

Fig. 4. Microstructure of steels 17G1s-U (*a*) and 10G2FB (*b*).

Under the condition that N_f, Mn, and Si are equal for different grades of steel and that *d* varies from 15 – 20 to 5 – 10 μm, the strengthening as a result of grain refinement ($\Delta\sigma_{\mathrm{g}}$) attains 150 MPa.

The dislocation structure forms in the stage of rolling and subsequent cooling. Since rolled products from the studied steels are obtained in the same equipment, we can expect that the dislocation density in different steels is about the same. Let us assume that this factor virtually does not change the yield strength and, therefore, $\Delta\sigma_{\mathrm{d}} = 0$.

In order to compute the strengthening due to fine particles we should have data on their size and volume fraction. The absence of such data is explainable by objective methodological aspects. However, the value of $\Delta\sigma_{\mathrm{f.p}}$ can be determined analytically as a difference between the actual hardening $\Delta\sigma_{0.2} = \sigma_{0.2(\mathrm{10G2FB,\ 12G2SB})} - \sigma_{0.2(\mathrm{17G1S\text{-}U})}$ and the contribution of all the other factors, namely, $\Delta\sigma_{\mathrm{s.s}}$, $\Delta\sigma_{\mathrm{p}}$, $\Delta\sigma_{\mathrm{g}}$, and $\Delta\sigma_{\mathrm{d}}$. With such an approach, $\Delta\sigma_{\mathrm{f.p}} = 70$ MPa.

The effect of various factors on the change in the yield strength is generalized in Table 2. It follows from these data that the most substantial contribution to the growth in the yield strength of low-carbon steels 10G2FB and 12G2SB is ensured by grain refinement. The mechanisms mentioned affect the impact toughness with different intensities. Table 2 also presents data on the effect of each of the mechanisms on the position of the cold-shortness threshold computed with the help of known empirical dependences [13]. It can be seen that grain refinement is the only possibility for lowering the temperature of the ductile-to-brittle transition in the steels studied; this is manifested in the elevated values of the impact toughness (see Fig. 1).

TABLE 2. Variation of the Yield Strength $\Delta\sigma_{0.2}$ and of the Temperature of the Ductile-to-Brittle Transition ΔT under the Action of Different Mechanisms of Strengthening of the Studied Steels

Mechanism of strengthening	$\Delta\sigma_{0.2}$, MPa	ΔT, °C
Solid-solution hardening of ferrite	– 40	– 20
Hardening due to pearlite	0	– 20
Hardening as a result of grain refinement	150	– 80
Hardening due to segregation of fine particles	70	20
Total change	180	– 100

CONCLUSIONS

1. The advantages of steels 10G2FB and 12G2SB over steel 17G1S-U consist in the elevated level of the yield strength and impact toughness unattainable for 17G1S-U, better combination of the strength and ductile characteristics, and lower temperature of the ductile-to-brittle transition.

2. The most significant structural factors determining the mechanical properties of steels 10G2FB and 12G2SB after controlled rolling are the grain size (refinement) and the segregation of fine particles.

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REFERENCES

1. N. P. Lyakishev, M. N. Kantor, A. A. Belkin, and V. N. Timofeev, “Estimation of the effect of long-term operation on mechanical properties and structure of the metal of delivery pipes,” *Zavod. Lab.*, No. 1, 75 – 83 (2007).
2. V. M. Schastlivtsev, T. I. Tabatchikova, I. L. Yakoveva, et al., “Structure and mechanical properties of rolled sheets from low-carbon low-alloy steels after thermomechanical treatment,” *Deform. Razrush. Mater.*, No. 10, 5 – 12 (2006).
3. M. I. Goldshtein and V. M. Farber, *Precipitation Hardening of Steel* [in Russian], Metallurgiya, Moscow (1979).
4. R. Lagneborg, T. Sivetski, S. Zayats, and B. Hatchitson, *Role of Vanadium in Microalloyed Steels* [in Russian], Izd. Tsentr “Maria,” Ekaterinburg (2001).
5. F. Heisterkami, K. Hulka, Yu. I. Matrosov, et al., *Niobium-Bearing Low-Alloy Steels* [in Russian], Intermet Engineering, Moscow (1999).
6. L. I. Efron, V. I. Il’inskii, A. V. Golovanov, and Yu. D. Morozov, “The physical metallurgy of fabrication of pipe steels by high-temperature controlled rolling,” *Stal’*, No. 6, 69 – 72 (2003).
7. M. V. Pridantsev, L. N. Davydova, and I. A. Tamarina, *Structural Steels* [in Russian], Metallurgiya, Moscow (1980).
8. N. P. Lyakishev, Yu. L. Pliner, and S. I. Lappo, *Boron-Bearing Steels and Alloys* [in Russian], Metallurgiya, Moscow (1986).
9. V. M. Schastlivtsev, I. L. Yakovleva, N. A. Tereshchenko, et al., “Special features of chemical composition and structure of low-carbon low-alloy pipe steels after controlled rolling,” *Metalloved. Term. Obrab. Met.*, No. 5, 3 – 8 (2008).
10. G. E. Kodjaspirov, V. V. Rybin, and H. Apostolopoulos, “Role of mesostructure in thermomechanical treatment of metallic materials,” *Metalloved. Term. Obrab. Met.*, No. 1, 30 – 34 (2007).
11. Ya. B. Fridman, *Mechanical Properties of Metals* [in Russian], Mashinostroenie, Moscow (1974).
12. M. P. Efimova, *Statistics* [in Russian], Infa-M, Moscow (2003).
13. D. A. Pumpyanskii, I. Yu. Pyshmintsev, and V. M. Farber, “Methods for hardening pipe steels,” *Stal’*, No. 7, 67 – 74 (2005).
14. F. B. Pickering, *Physical Metallurgy and Design of Steels* [in Russian], Metallurgiya, Moscow (1982).