Development and research of forming the properties in cold resistant steels with strength class not less than 950 MPa for the components of heavy carrying and lifting machines

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The paper presents new high-strength steels for the components of heavy carrying and lifting machines, which operates in the Far North and Arctic areas. Combination of the main parameters of the developing steels leaves behind the existing global analogues and demonstrates high strength, ductility as well as cold resistance at the temperature down to –70 °C: tensile strength not less than 1,200 MPa, yield strength not less than 950 MPa, relative elongation not less than 10 %, hardness not less than 350 HBW, impact strength KCV^{-70} not less than 30 J/cm^2. 4 steel chemical compositions on the base of C–Mn–Mo alloying system with additives of nickel and copper as well as microalloying elements, which were used together or separately, are examined in this research. Thermokinetic diagrams of decomposition of overcooled austenite were built and temperature-temporal conditions of forming of bainite-martensite structure were determined; these conditions are related for the new high-strength cold-resistant steels containing 0.17–0.21 % C; 0.70–1.30 % Mn; 0.25–0.35 % Si and 0.28–2.00 % (Ni+Cu+Mo). Influence of varying chemical composition on phase transformations and structure during continuous cooling of the examined steels was established and the heat treatment procedure for achievement of the required construction strength (combination of high tensile strength and low temperature impact strength) was suggested. As a result, it was determined that the most wide range of cooling rate values for obtaining of bainite-martensite structure (not less than 10 °C/c) and the optimal complex of strength and toughness-ductile properties are provided in the steel with the following chemical composition (mass. %): 0.21 C; 0.30 Si; 0.73 Mn; 0.017 Cr; 2.00 (Ni+Cu+Mo); 0.027 Ti; 0.003 B after quenching from 860 °C.

Key words: cold-resistant steel, alloying system, alloying elements, thermokinetic diagram, phase and structural transformations, high strength, cold resistance, quenching.
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Introduction

The new high-strength steels for the components of heavy carrying and lifting machines, which operates in the Far North and Arctic areas were developed during recent years in Nosov Magnitogorsk State Technical University [1–4]. Influence of low temperatures, dynamic and cyclic loads during equipment operation in these regions stipulate more strict requirements to mechanical properties of steels for manufacture of mechanisms, machines and constructions for special applications [5–7]. The materials presented in this paper continue the cycle of researches on examination of structural and phase transformations, which occur in the new high-strength cold-resistant steels, and forming of a unique complex of mechanical properties of these steels.

The principles of development of high-strength cold-resistant steels and features of forming of their mechanical properties were examined and rather thoroughly presented in national and foreign technical literature [3, 4, 8–11]. At the same time, development of high-strength cold-resistant steels with tensile strength level not less than 950 MPa is quite actual, and combination of the main parameters of these steels will exceed the existing world analogues. They will present combination of high strength, ductility and cold resistance at the temperature down to -70 °C: tensile strength not less than 1,200 MPa, yield strength not less than 950 MPa, relative elongation not less than 10 %, hardness not less than 350 HBW, impact strength KCV^{-70} not less than 30 J/cm^2.

Taking into account the above-mentioned data, development and research of forming of structure and properties of the new cold-resistant steels with tensile strength level not less than 950 MPa on the base of choosing chemical composition and examination of regularities of structural and phase transformations is the aim of this work.

Research methods

Taking into consideration the well-known principles of steel creation with yield strength more than 950 MPa for achievement of the most high complex of mechanical properties, the research was aimed on forming of bainite-martensite structure in new steels, through whole thickness of rolled products. In this connection, the concepts of steel alloying were chosen, meaning that these concepts are potentially able to form such structures and, respectively, to provide the required combination of properties ($\sigma_{0.2} \geq 950$ MPa, $\sigma_{\text{в}} \geq 1{,}200$ MPa, $\delta_5 \geq 10\,\%$, HBW ≥ 350, $KCV^{-70} \geq 30$ J/cm^2). 4 steel chemical compositions on the base of C–Mn–Mo alloying system with additives of nickel and copper as well as microalloying elements, which were used together or separately, were chosen on the base of the search results.

The processes of melting, continuous casting, deformation and heat treatment of steel with selected chemical composition were carried out using the equipment of the scientific and production complex of "Its Termodeform-MGTU". The billets with size 300 × 90 × 90 mm were subjected to deformation to thickness 13 mm with the following temperature procedures: the roughing step-by-step deformation with maximal billet temperature 1250 °C and the finishing stage with deformation degree not less than 13 % per pass with the finishing rolling temperature 850–950 °C. Implementation of rather high average values of relative reduction per pass provides forming of homogeneous fine-dispersed austenite structure, which is inherited during quenching and has the effect on structure dispersity after heat treatment.

Study of decomposition kinetics for overcooled austenite of steels using the complex Gleeble 3500 as well as metallographic researches were carried out in the Centre of common use at "Nanosteels" Scientific and research institute of Nosov Magnitogorsk State Technical University. Heating and cooling experiments for a steel were conducted in the Pocket Jaw module of this complex with switched-on system for dilatometric testing. Heating of the samples with diameter 10 mm was implemented in vacuum up to the temperature 950 °C with consequent cooling at the rates within the range from 1 to 110 °C/s.

Qualitative and quantitative analysis were carried out via a light microscope Axio Observer (Zeiss), using the software Thixomet PRO for processing of metallographic images, as well as via scanning electronic microscope (SEM) JSM 6490 LV.

Testing for stretching, impact bending and hardness measuring via Brinnell and Vickers were carried out according to the standard techniques.

Results of the researches and discussion

Chemical composition of the pilot melts for developed steels is presented in the **Table 1**.

Choosing the intervals of elements content in composition of the developed steels was based on the following principles:

– 0.17–0.21 % C provides weldability, high parameters of ductility and high-temperature impact strength as well as lowering of the risk of quenching cracks forming;

– 0.70–1.30 % Mn and 0.25–0.35 % Si guarantees solid solution strengthening and required hardenability;

– 0.10–0.30 % Mo increases stability of overcooled austenite and provides satisfactory weldability;

– (Ni+Cu+Mo) ≤ 2.5 % provides high parameters of ductility and high-temperature impact strength (down to -70 °C).

– 0.003–0.004 % B increases hardenability;

– 0.020–0.030 % Ti hinders grain growth during heating as well as binds nitrogen and evacuate it out of solid solution, what allows to save the most part of boron in active state.

The regularities of phase and structural transformations were established for the new compositions of the molten steels, based on the results of complex dilatometric and metallographic analyses as well as hardness measurement. These transformations occur in steels during continuous cooling. Afterwards, thermokinetic diagrams of overcooled austenite (**Fig. 1**) and structural diagrams (**Fig. 2**) were built.

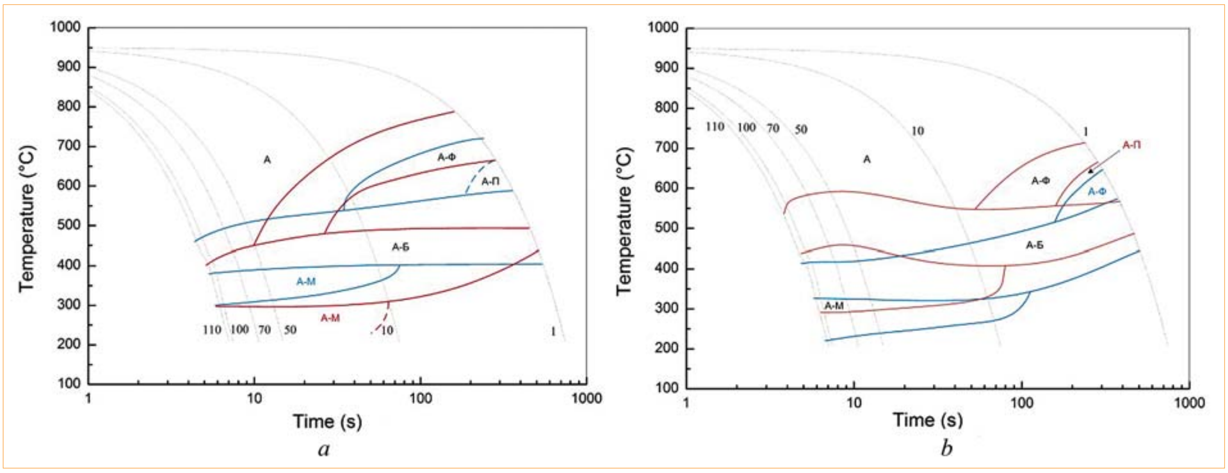
Ferrite, pearlite, bainite and martensite transformations are realized in the steels with pilot compositions No. 1–3. Ferrite transformation takes place in the wide range of cooling rates from 1 to 50 °C/s in the steel with composition No. 1 with minimal alloying (red diagram in the Fig. 1*a* and 2*a*), with low (0.85 %) Mn content and absence of Ni and Cu additives; in this case pearlite transformation occurs in the range of cooling rates from 1 to appr. 20 °C/s. At the same time, bainite transformation is realized just at the most low cooling rate, what is caused by Mo presence in steel as an alloying element. Starting from cooling rate about 10 °C/s, martensite is revealed in the structure, its amount is small at this cooling rate (Fig. 2*a*). Bainite-martensite structure without products of diffusion transformation is realized at the cooling rate above 50 °C/s.

Increase of manganese content up to 1.29 % (composition No. 1) leads to rise of stability of overcooled austenite within the temperature range of pearlite transformation: ferrite and pearlite transformations are realized only at the cooling rates not higher than 10 °C/s and 3 °C/s respectively (see blue diagram in the Fig. 1*a*), while bainite-martensite transformation is formed already at the cooling rate 10–15 °C/s (see Fig. 2*b*).

Introduction of γ-stabilized elements (nickel and copper) in steel with compositions No. 3 and No. 4, with low

Table 1. Chemical composition of the pilot steels

No. of composition	Part of the elements, mass. %							
	C	Si	Mn	Cr	Ni+Cu+Mo	Al	Ti	B
1	0.21	0.35	0.85	0.01	0.28	0.044	–	–
2	0.18	0.31	1.29	0.06	0.32	0.050	–	–
3	0.17	0.28	0.82	0.02	1.52	0.042	0.024	0.0032
4	0.21	0.30	0.73	0.02	2.00	0.035	0.027	0.0030



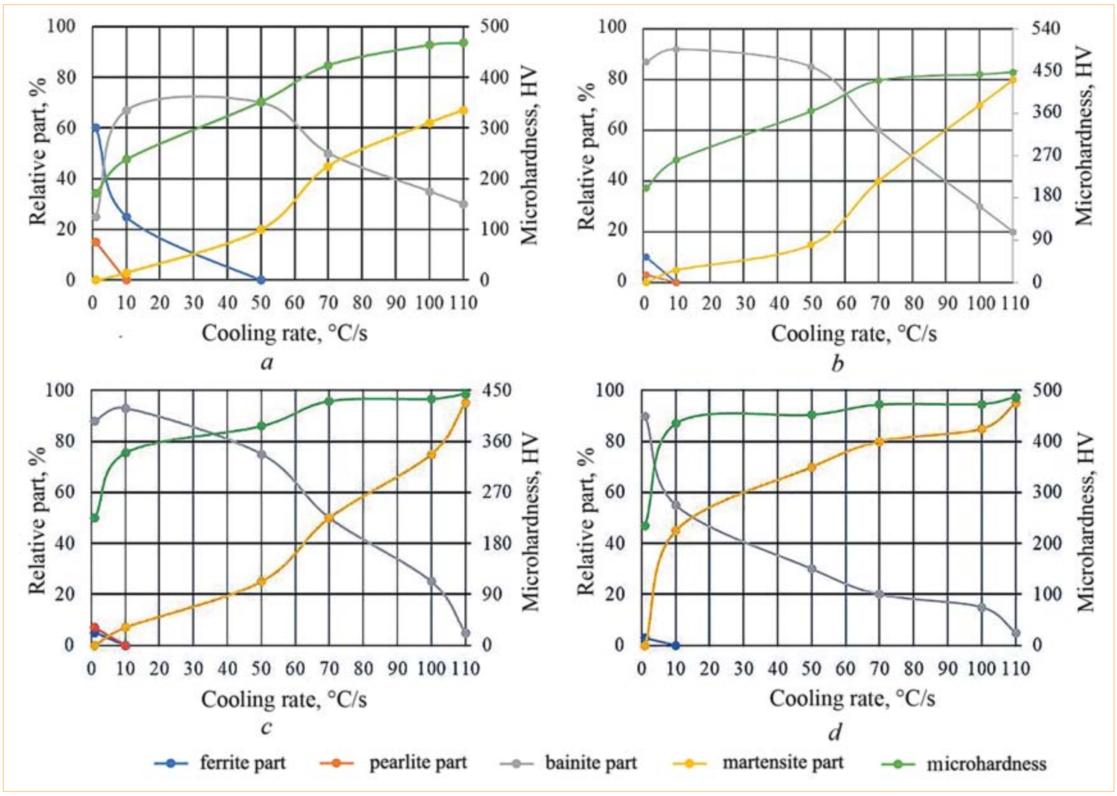
a

b

Fig. 1. Thermokinetic steel diagrams:

a – red diagram of the composition No. 1 (0.85 % Mn + 0.28 % (Ni+Cu+Mo); blue diagram of the composition No. 2 (1.29 % Mn + 0.32 % (Ni+Cu+Mo);

b – red diagram of the composition No. 3 (0.82 % Mn + 1.52 % (Ni+Cu+Mo) + 0.027 % Ti + 0.003 % B; blue diagram of the composition No. 4 (0.73 % Mn + 2.00 % (Ni+Cu+Mo) + 0.029 % Ti + 0.003 % B



a

b

c

d

Fig. 2. Structural diagrams:

a – composition No. 1 (0.85 % Mn + 0.28 % (Ni+Cu+Mo);

b – composition No. 1 (1.29 % Mn + 0.32 % (Ni+Cu+Mo);

c – composition No. 3 (0.82 % Mn + 1.52 % (Ni+Cu+Mo) + 0.027 % Ti + 0.003 % B;

d – composition No. 4 (0.73 % Mn + 2.00 % (Ni+Cu+Mo) + 0.029 % Ti + 0.003 % B

manganese content (0.73–0.82 %), stabilizes austenite in the temperature range of diffusion transformation (see Fig. 1*b*). Introduction of 1.52 % (Ni+Cu+Mo) additive in steel with composition No. 3 leads to realization of ferrite and pearlite transformation only at the cooling rates up to 10 °C/s and not higher than 5 °C/s respectively (see red diagram in the Fig. 1*b* and Fig. 2*c*). Increase of mass part of nickel and copper in steel with composition No. 4 (up to 2.00 % of (Ni+Cu+Mo)) mainly stabilizes austenite in the temperature range of diffusion transformation: ferrite transformation is observed only at the cooling rate up to 3 °C/s, pearlite transformation is suppressed completely, even at the low cooling rate 1 °C/s (see blue diagram in the Fig. 1*b* and Fig. 2*d*).

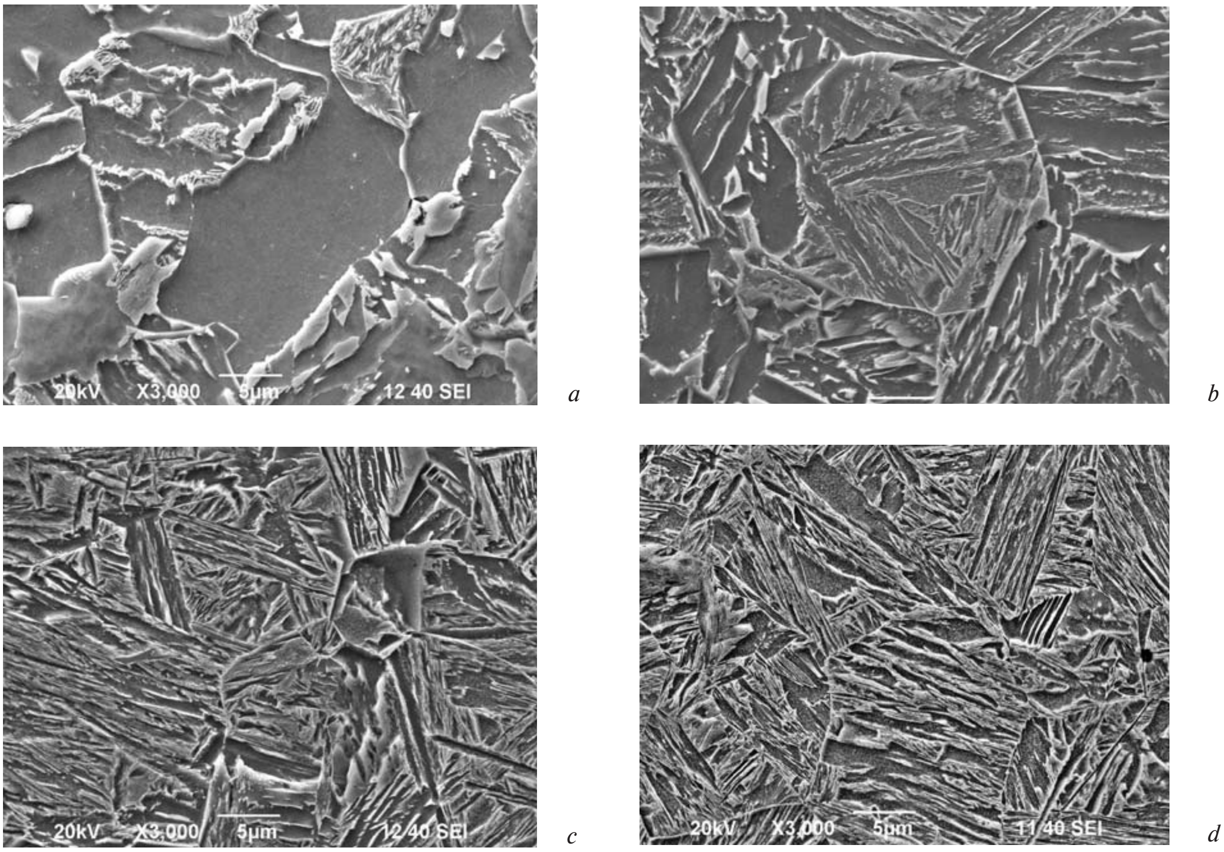


Fig. 3. Microstructure of steel with composition No. 1 (1.29 % Mn + 0.32 % (Ni+Cu+Mo)), formed at the following cooling rates: *a* – 1 °C/s; *b* – 10 °C/s; *c* – 50 °C/s and *d* – 110 °C/s

Typical microstructures of the examined steels, which were formed during continuous cooling, are presented in the **Fig. 3**. Steel structure with composition No. 2 (1.29 % Mn + 0.32 % (Ni+Cu+Mo)) is characterized by grains of polygonal ferrite and granular bainite at the cooling rate 1 °C/s. This granular bainite consists of α-phase crystals, with second phase located inside them; that second phase is presented mainly by M/A areas and small amount of pearlite areas (Fig. 3*a*). Ferrite in the form of separate grains or islands, bainite with regular and lath morphology as well as martensite are presented in the microstructure at the cooling rate 10 °C/s (Fig. 3*b*). Pearlite is not found out in microstructure, what testifies on its complete suppression at this cooling rate. Lath bainite constitutes elongated laths of α-phase, which are organized in packs with cementite located along lath boundaries. At the cooling rate 50 °C/s, bainite and martensite are presented in microstructure after ferrite transformation. Bainite is identified mainly as upper bainite with lath morphology. Martensite component of a sample microstructure meaning its morphology can be mainly classified as lath and high-temperature lamellar martensite (Fig. 3*c*). At the cooling rate 110 °C/s, amount of martensite makes 80 % and amount of bainite – 20 % (Fig. 3*d*). Similar structures were observed in the steels with other pilot compositions. The difference concluded in the range of cooling rates, at which these structure were formed.

Analysis of the thermokinetic diagrams displayed that the cooling rate, which provides obtaining of bainite-martensite structure in the steels with developed compositions, should be not less than 50 °C/s. It was established in this case that it is required to provide cooling of the examined steels with compositions No. 1–3 and with composition No. 4 with the cooling rates not less than 50 °C/s and 10 °C/s respectively, in order to achieve hardness exceeding 350 HBW (360 HV). Such cooling rates during processing of rolled sheets can be provided via quenching in water. To create high-strength cold-resistant steels, which are used for heavy carrying and lifting machines, it is necessary to take into account the idea that quenching from separate furnace heating starting from the temperature above A_{C3} by 30–50 °C is preferable [12, 13]. Additionally, attention should be paid for the technical and technological possibilities of the roller heating furnace of the 5000 rolling mill in the industrial conditions of Magnitogorsk Iron and Steel Works during development of recommendations for heat treatment. Based on this conclusion, the heating temperature for quenching was chosen as minimal possible and constituted 860 °C, what was also determined by necessity of forming fine-grained austenite during heating [14, 15].

The results of mechanical testing of laboratorial samples of rolled products after quenching from 860 °C are presented in the **Fig. 4**.

Analysis of the obtained data (Fig. 4*a*) proved that high values of mechanical properties are achieved in all steels with examined chemical compositions after quenching in water from 860 °C. These mechanical properties meet the

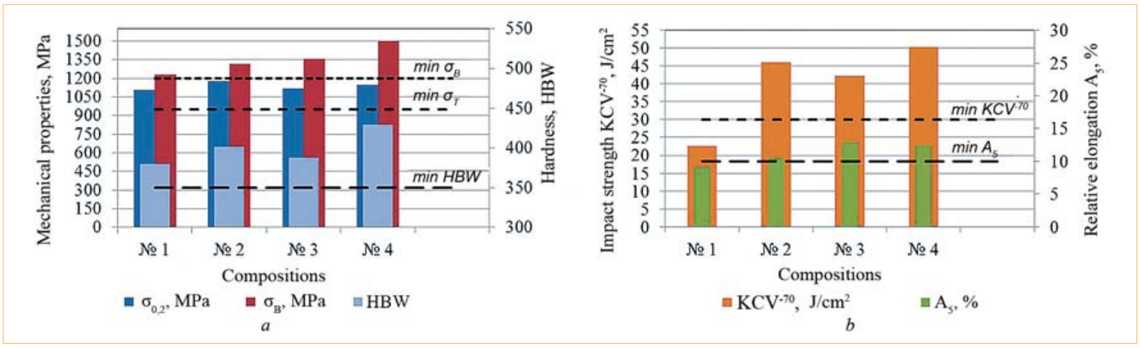


Fig. 4. Mechanical properties of steels after quenching in water from 860 °C (dotted lines displayed the prescribed level): *a* – tensile strength, yield strength, hardness; *b* – impact strength, relative elongation

requirements to the developed materials, what is stipulated fy forming of mixed bainite-martensite structure. Presence of molybdenum in the examined steels promotes forming of bainite phase in the structure of quenched steel and, as known, provides favourable effect on resistance to brittle destruction in high-strength low-carbon steels [16]. At the same time, maximal value of tensile strength (σ_B = 1,500 MPa) and hardness 430 HBW are achieved in the steel with composition No. 4, with maximal carbon content 0.21 % and total amount of nickel and copper additives 2.0 % of Ni+Cu+Mo.

The most high values of yield strength are achieved in the steel with composition No. 2, with carbon content 0.18 % and the most high manganese content 1.29 %, what is explained by the effect of strengthening in solid solution. The samples of the steels with compositions No. 1, 3 and 4 with smaller manganese content (0.75–0.85 %) are characterized by lower values of yield strength.

Maximal resistance to impact loads at the temperature -70 °C was also obtained in the samples of the steel with composition No. 4 (Fig. 4*b*), what is explained by low manganese content 0.73 % and high content of (Ni+Cu+Mo) – 2.00 %. Such manganese content provides strengthening of solid solution and does not cause decrease of brittle destruction resistance [6, 7, 10, 17–22]. The samples of the steel with composition No. 1 are characterized by essentially lower impact strength, what is connected with higher carbon and manganese content (0.21 % and 0.85 % respectively) and smaller content of (Ni+Cu+Mo) (0.28 %). At the same time, it was established that if summarized content of (Ni+Cu+Mo) exceeds 1.52 %, it will not provide any advantages in comparison with impact strength for high manganese content 1.29 % (Fig. 4*b*).

Based on the above-described considerations, it can be noted that the most wide range of cooling rates for obtaining of bainite-martensite structure (not less than 10 °C/s) and the optimal complex of strength and tough-ductile properties are provided in the steel with the following actual chemical composition (mass. %): 0.21 C; 0.30 Si; 0.73 Mn; 0.017 Cr; 2.00 (Ni+Cu+Mo); 0.027 Ti; 0.003 B after quenching from 860 °C.

Conclusions

1. Thermokinetic diagrams of decomposition of overcooled austenite were built and temperature-temporal conditions of forming of bainite-martensite structure were determined; these conditions are related for the new high-strength cold-resistant steels containing 0.17–0.21 % C; 0.70–1.30 % Mn; 0.25–0.35 % Si and 0.28–2.00 % (Ni+Cu+Mo). Influence of varying chemical composition on phase transformations and structure during continuous cooling of the examined steels was established and the heat treatment procedure for achievement of the required construction strength (combination of high tensile strength and low temperature impact strength) was suggested.

2. The study of phase and structural transformations displayed that mixed bainite-martensite structure is observed in the steels with chosen chemical compositions at the cooling rates not less than 50 °C/s. In this case, in order to achieve hardness exceeding 350 HBW (360 HV), it is required to cool the examined steels with composition (Ni+Cu+Mo) < 2,0 % and with higher Ni+Cu+Mo composition at the cooling rates not less than 50 °C/s and 10 °C/s respectively. It guarantees obtaining of bainite-martensite structure without forming of diffusion transformation products through whole thickness of rolled products.

3. It was established that forming of bainite-martensite structure in all examined steels after quenching from 860 °C leads to achievement of the required complex of strength and tough-ductile properties: tensile strength not less than 1,200 MPa, yield strength not less than 950 MPa, relative elongation not less than 10 %, hardness not less than 350 HBW, impact strength KCV^{-70} not less than 30 J/cm². The best complex of mechanical properties (σ_T=1,150 MPa, σ_B=1,500 MPa, δ_5=12.5 %, HBW=429, KCV^{-70}=50.3 J/cm²) is provided in the steel with the following chemical composition (mass. %): 0.21 C; 0.30 Si; 0.73 Mn; 0.017 Cr; 2.00 (Ni+Cu+Mo); 0.027 Ti; 0.003 B.

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