Research of phase and structural transformations and properties in high-strength cold resistant steels for machine-building

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The requirement in domestic high-strength cold-resistant materials increases at present time, what has positive effect on development of Russian economics. Creation of import-substituting high-strength cold-resistant steels allows to provide leading positions of national machine-building manufacturing equipment for operation in the extremal conditions of Far North and Arctic region. Regularities of phase and structural transformations in the new experimental high-strength cold-resistant steel, occurring during continuous cooling, are established and thermokinetic diagram of decomposition of overcooled austenite is built.To realize consequent mastering of the new steel in industrial conditions, laboratorial samples of rolled products were fabricated and the quenching procedure for rolled sheet metal in water from the temperature 860 ^{0}C was tested using specialized equipment of the laboratorial complex of Nosov Magnitogorsk State Technical University. It is shown that the experimental steel is characterized by high complex of mechanical properties after suggested heat treatment, owing to forming of fine-dispersed microstructure of lath martensite (up to 85 %) and bainite (up to 15 %). In this case martensite provides high strength of the researched steel ($\sigma_в$ = 1,440 MPa, $\sigma_{0,2}$ = 1,380 MPa), while presence of dispersed structure of low-carbon bainite ensures high parameters of destruction resistance (KCV^{-70}=59 J/cm^2). Hardness more than 429 HBW (455 HV) is achieved by cooling with the speed exceeding 100 ^{o}C/s. The obtained complex of mechanical properties displays possibility of using the new experimental high-strength cold-resistant steel for manufacture of heavy-loaded constructions in machine-building, which are operated at low temperatures of Far North and Arctic region.
Key words: high-strength cold-resistant steel, continuous cooling, phase transformations, thermokinetic diagram, structure, hardness, quenching, low-temperature toughness.
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Introduction

The market requirements to modern materials for machine-building are increasing permanently. Customers need new materials which can combine at the same time high strength, ductility and cold resistance; it allows to decrease material intensity and to enlarge service life of various products and equipment operating in the extremal Far North conditions [1, 2].

At present time the researches aimed on development of the new chemical compositions of high-strength steels are continuously carried out by domestic and foreign producers as well as scientific and research centers. Creation of new import-substituting high-strength cold-resistant steels will meet the requirements of national machine-building in the field of manufacturing the equipment for operation in the extremal conditions of Far North and Arctic region [3–11].

Products of Magnitogorsk Iron and Steel Works, one of the leaders of the Russian market of high-strength cold-resistant steels, became a response to the formulated tasks of strategic development aimed on creation of new steel grades; it can be competitive to world analogues. At present time, the specialists of Nosov Magnitogorsk State Technical University are developing the new technology for manufacturing steels for heavy-loaded constructions in machine-building, operating in the extremal Far North conditions, to be put into practice at Magnitogorsk Iron and Steel Works. Such steel is characterized by the following combination of mechanical properties: tensile strength ≥ 1,200 MPa; yield strength ≥ 950 MPa; relative elongation $\delta_5 \geq 10$ %; HBW hardness ≥ 350; impact strength KCV ≥ 30 J/cm^2 at the temperature 70 ^{0}C [4, 12, 13]. Provision of such complex of mechanical properties is possible during definite structural and phase transformations occurring in steel.

Based on the above-described conclusions, the aim of this research is formulated as investigation of the features of phase and structural transformations during continuous cooling and of forming the properties of the new high-strength cold-resistant steel, as well as preparing the recommendations for putting into practice scientific and practical results in the conditions of leasing metallurgical works.

Materials and methods

The research was carried out with laboratorial steel samples having the following chemical composition, % (mass.): 0.22 C, 0. 32 Si, 0.75 Mn, 1.5 (Ni+Cu+Mo), 0.075 (Ti+V+Nb). The samples of hot-rolled sheets were subjected to melting, hot rolling and consequent heat treatment using the equipment of scientific and production complex "Termodeform-MGTU".

Metallographic researches as well as experiments on steel heating and cooling were carried out 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, using the Pocket Jaw module of the complex Gleeble 3500, equipped with switched-on system for dilatometric testing. Heating of the samples with diameter 10 mm up to austenite state was implemented in vacuum up to the temperature 950 °C with consequent cooling at the rates within the range from 1 to 200 °C/s. These speed rates can be realized in the pilot-industrial conditions of rolling of such steel products. Building of thermokinetic diagrams was conducted in automatic mode, using add-in software to the standard software package Origin®, built in the system Gleeble 3500.

Polished sections for microanalysis were fabricated according to the standard technique in the Buehler sample preparation line. A light microscope Zeiss Axio Observer, using the software Thixomet PRO for processing of metallographic images as well as via scanning electronic microscope (SEM) JSM 6490 LV were used for microstructure analysis. Quantitative analysis was carried on light and electron microscope microstructure images using the software complex Thixomet PRO. Testing for hardness of the samples was carried out using Buehler Mikromet hardness meter via Vickers method (indenting of a diamond pyramid with the angle 136° between opposite planes, with load 1,000 g and loading duration 10 s).

Fabrication of laboratorial rolled samples for mechanical testing was conducted according to the GOST 7564-97 using specialized equipment of "ITs Termodeform-MGTU". Extension testing was carried out on flat 5-fold samples of the type II with full thickness according to the GOST 1497-84 in universal testing machine of ZWICK GmbH&Co, Z2000 series. Impact bending testing at the temperature –70 °C was implemented according to the GOST 9454-78 on the samples of the type II using a pendulum impact machine RKP 450. Brinnell HBW hardness testing was carried out according to the GOST 9012-59 using a hard alloy ball with diameter 10 mm, under the force F = 29,420 N (3,000 kgf).

Results and discussion

Critical temperatures of phase transformations, which were determined with use of differential scanning calorimetry, were equal to $A_{c1} \approx 723$ °C, $A_{c3} \approx 829$ °C. Analysis of dilatometric cooling curves displayed the registered folds which allow to determine the temperatures of the following phase transformations: ferrite extraction from austenite as well as pearlite, bainite and martensite transformations (see the **Table 1**). Microstructure, which was formed after controlled cooling with different rates from the temperature 950 °C, is presented in the **Fig. 1**, the results of quantitative analysis of microstructure and hardness determination in the **Table 2**.

Table 1. Temperatures of phase transformations of the examined steel during continuous cooling

Cooling rate, °C/s	Temperatures of phase transformations, °C						
	Ferrite transformation	Pearlite transformation		Bainite transformation		Martensite transformation	
	Start	Start	End	Start	End	Start	End
1	768	675	584	584	407	407	339
10	769	690	601	601	411	411	315
50	736	–	–	647	431	431	297
70	734	–	–	665	435	435	274
100	715	–	–	645	435	435	266
130	–	–	–	608	437	437	258
150	–	–	–	567	408	408	258
200	–	–	–	–	–	430	246

Table 2. Quantitative indicators of microstructure and steel hardness after cooling with different rates

Cooling rate, °C/s	Relative volumetric part of structural components, %				Hardness, HV
	Ferrite	Pearlite	Bainite	Martensite	
1	55	20	20	5	201
10	15	5	75	5	249
50	10	0	65	25	351
70	7	0	43	50	380
100	5	0	25	70	415
130	0	0	15	85	465
150	0	0	5	95	471
200	0	0	0	100	475

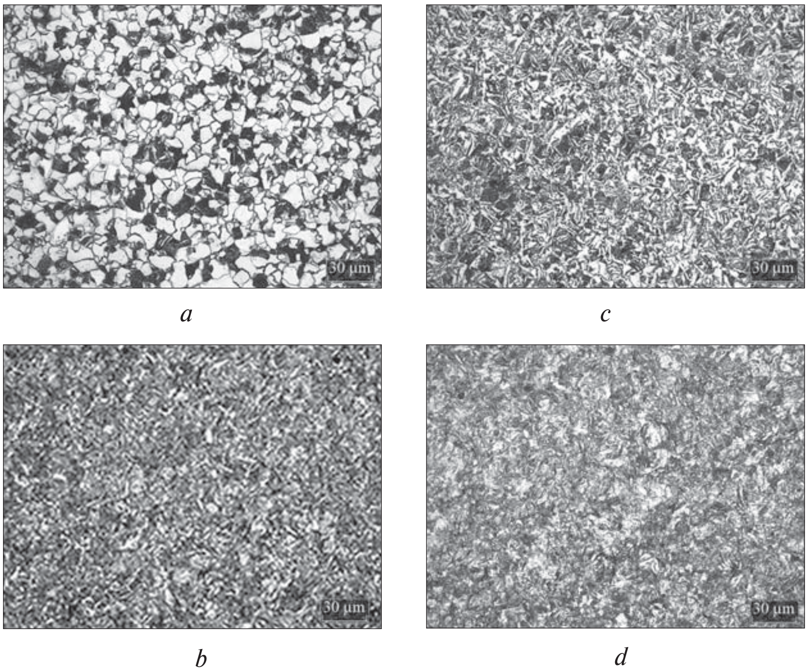

Fig. 1. Steel microstructure after cooling with rates 1 °C/s (*a*), 10 °C/s (*b*), 50 °C/s (*c*) and 200 °C/s (*d*), ×500

Steel structure after cooling with the rate 1 °C/s is characterized by reveal of polygonal ferrite grains and dark component, which can't be identified via the method of scanning electron microscopy (see the Fig, 1, *a*). When cooling rate is 10 °C/s, ferrite is also revealed in the structure, but in smaller amount, as separate grains and net along grain boundaries. The dark component (see the Fig, 1, *b*) is also revealed, the results of more detailed examination are presented below. At the same time, at cooling rate 10 °C/s and higher, the structure with lath features, typical for quenched steel, is observed in the samples (see the Fig, 1, *b–d*).

To provide detailed identification of the structural components and reveal of their morphology, SEM examination was carried out (see the results in the **Fig. 2**).

Analysis of the obtained data displayed that cooling rate 1 °C/s is accompanied by observation of polygonal ferrite in microstructure (Fig. 2, *a*) in the amount 55 %, while pearlite and bainite of various morphology (Fig. 2, *a*, *b*) and martensite (Fig. 2, *b*) are observed in the dark areas via an optical microscope (Fig. 1, *a*). The amount of pearlite and bainite makes 20 %, the amount of martensite – 5 %. Granular bainite (B_{gr}) consists of α-phase with pearlite and austenite-

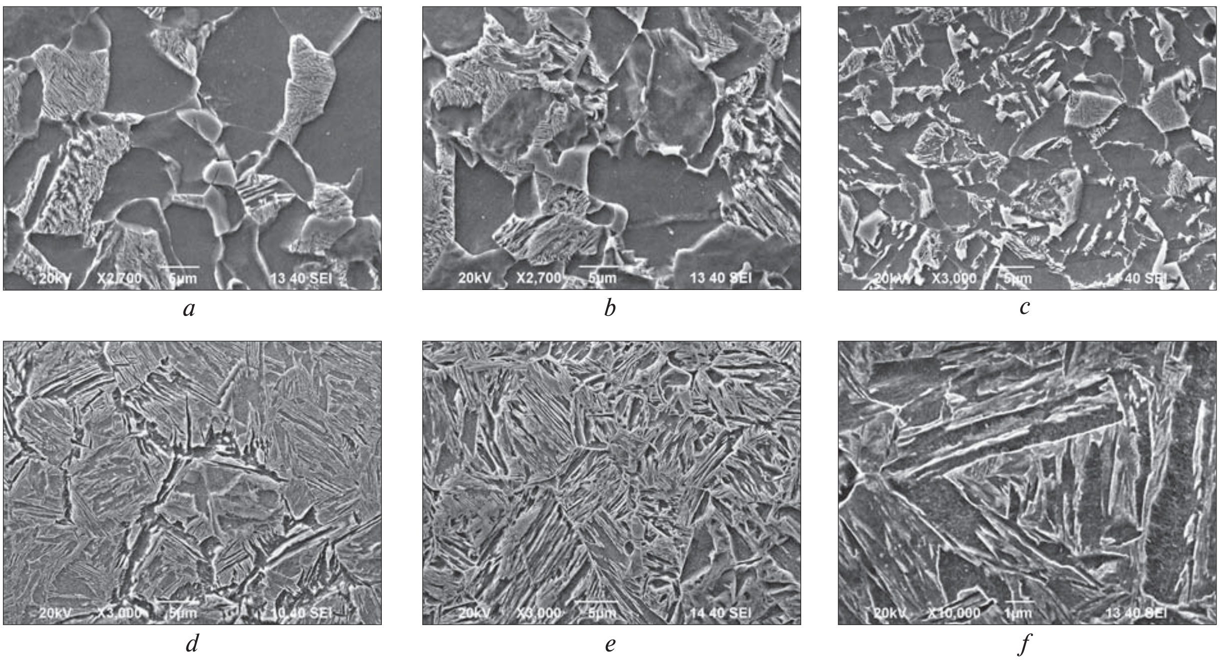

Fig. 2. Features of steel microstructure components after cooling with rates 1 °C/s (*a*, *b*), 10 °C/s (*c*), 70 °C/s (*d*) and 150 °C/s (*e*, *f*), × 500

martensite areas located inside this phase (Fig. 2, *b*). Such bainite components are most widely distributed structural elements of bainite [14, 15]. Lathe bainite (B_l) is presented by elongated lathes of α-phase, which are organized in packages with cementite and located along the boundaries of lathes (Fig. 2, *a*, *b*).

Cooling rate 10 °C/s is characterized by ferrite in the form of separate grains in microstructure, while pearlite, bainite and martensite are identified in the dark areas (Fig. 2, *c*). Ferrite and pearlite parts in microstructure decreases down to 15 % and 5 % respectively, while bainite part increases up to 75 %. Bainite is morphologically identified as granular and lath bainite, which are presented in approximately equal parts. Additionally, up to 5 % of martensite in the form of rather coarse areas is observed in microstructure (Fig. 2, *c*).

Ferrite is presented in microstructure in the amount up to 7 % along the boundaries of bainite and martensite areas until achieving the cooling rate 70 °C/s; martensite part increases in this case up to 50 %, while bainite has mainly lath morphology (Fig. 2, *d*). Pearlite transformation is suppressed starting from the cooling rate 50 °C/s. When cooling rate makes 130 °C/s, ferrite is not observed in microstructure and martensite part increases up to 85 %, while the cooling rate 150 °C/s is accompanied by elevation of martensite amount up to 95 % (Fig. 2, *e*). Martensite is morphologically identified as lath martensite (M_l), where elongated lathes are collected in a package, and high-temperature lamellar martensite (M_{lm}), which is non-structural in its form and does not contain neither lathes nor plates, nor any other clearly marked separation boundaries inside (Fig. 2, *f*).

Based on the results of complex dilatometric and metallographic analyses and hardness measurements, the thermokinetic diagram (TKD) of overcooled austenite decomposition was built for the new experimental steel (**Fig. 3**). TKD analysis displayed that the upper critical cooling rate, which provides forming of martensite structure, makes about 200 °C/s, while the critical cooling rate, which provides forming of bainite-martensite structure, exceeds 130 °C/s. It was established in this case, that the examined steel should

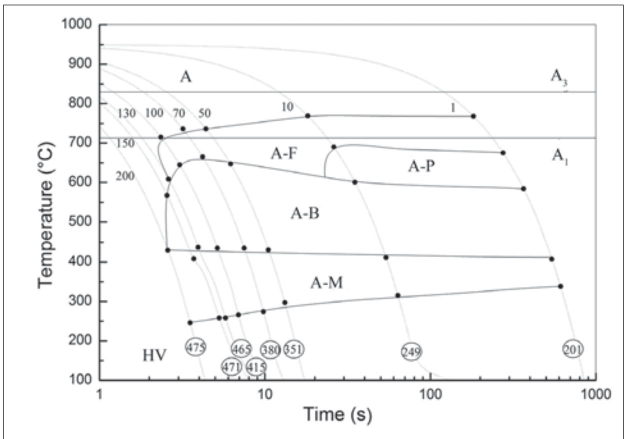

Fig. 3. Thermokinetic diagram of overcooled austenite transformation in steel (A – austenite, F – ferrite, P – pearlite, B –bainite, M – martensite)

be subjected to cooling from austenite state with the cooling rate not less than 50 °C/s, in order to achieve hardness exceeding 350 HBW (360 HV).

To provide durable and reliable operation in the conditions of increased wear and effect of impact loads (including those at the negative temperatures), high-strength cold-resistant steels should be characterized not only by high strength, but also by sufficient impact strength. It is known, that combination of high hardness and low-temperature impact strength can be provided after quenching and low tempering, or quenching for martensite [12, 13, 15–17]. Martensite ensures well wear resistance due to development of deformation dynamic ageing, which leads to efficient fixing of dislocations and intensive hardening [6, 12, 13, 15, 18, 19]. For example, high complex of mechanical properties – $\sigma_в$ = 1,729 MPa, $\sigma_{0.2}$ = 1,381 MPa, 495 HBW and KCV^{-40} = 45 J/cm² – was obtained in rolled steel sheets H500 MAGSTRONG® after quenching from the temperature higher by 30–50 °C than A_{c3}. This result was achieved owing to forming of advantageous (up to 75–80 %) lath martensite structure with width of lathes 0.1–0.5 μm, with high density of dislocations and with thin layers of residual austenite [12, 18, 19].

Lath martensite can provide high strength of the examined steel, while presence of dispersed structure – high parameters of destruction resistance [6, 12, 13, 18, 19]. TKD showed that cooling rate within the range 50–150 °C/s is required for obtaining martensite-bainite structure and for achieving hardness exceeding 350 HBW (360 HV) in the examined steel. Such cooling rate can be provided during water quenching. Choice of heat treatment procedures for the new steel was based on the fundamental regulations of the phase transformation theory and on the results of examination of structural and phase transformations in the experimental steel; technical and technological possibilities of the roller heating furnace at the 5000 rolling mill of Magnitogorsk Iron and Steel Works were also taken into account.

Laboratorial hot-rolled steel was subjected to heat treatment (water quenching from the temperature 860 °C) in order to achieve the required structural strength, a combination of high strength and low-temperature impact strength.

As a result, microstructure containing martensite package of fine-dispersed lathes (up to 85 %) and lath bainite (~15 %) was obtained (**Fig. 4**, ***a***); its morphological features can be seen clearly with large magnification (**Fig. 4**, ***b***). Additions of 0.075 % (Ti+V+Nb) in combination with 1.5 % (Ni+Cu+Mo) allowed to save fine-grained steel structure and to provide high indictors of ductility and low-temperature impact strength (to –70 °C) in high-strength steel: impact strength KCV^{-70} = 59 J/cm², relative elongation δ_5 = 13 %, tensile strength $\sigma_в$ = 1,440 MPa, yield strength $\sigma_{0,2}$ = 1,380 MPa, hardness 429 HBW.

Conclusion

The features of phase and structural transformations during continuous cooling were examined in the new experimental high-strength cold-resistant steel with the following chemical composition, % (mass.): 0.22 C, 0. 32 Si, 0.75 Mn, 1.5 (Ni+Cu+Mo), 0.075 (Ti+V+Nb). Thermokinetic

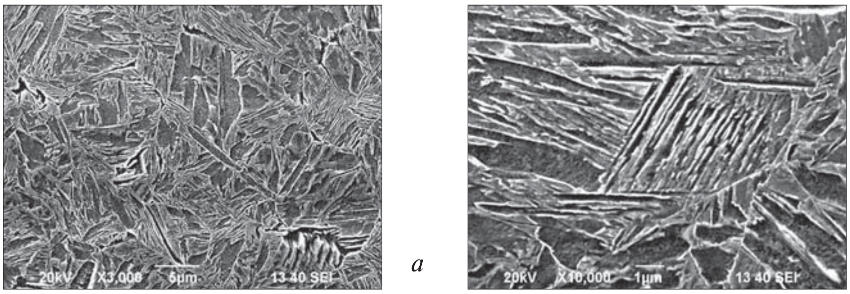

Fig. 4. Microstructure of rolled sheet samples of the new steel after quenching from 860 °C

diagram of overcooled austenite decomposition was built; it reflects kinetics of phase transformations and allows revealing the temperature and time intervals of structural transformations during cooling from 950 °C, with cooling rate from 1 to 200 °C/s.

It is displayed that the experimental steel has all required mechanical properties in combination with low temperature impact strength after water quenching from the temperature 860 °C; it occurs due to forming of fine-dispersed microstructure with lath martensite (up to 85 %) and bainite (up to 15 %). In this case martensite provides high strength of the examined steel ($\sigma_{\text{в}}$ = 1,440 MPa, $\sigma_{0.2}$ = 1,380 MPa), while presence of dispersed structure of low carbon bainite provides high indicators of destruction resistance (KCV^{-70} = 59 J/cm^2). Hardness exceeding 429 HBW (455 HV) is achieved via cooling with the rate above 100 °C/s.

The obtained complex of mechanical properties displays possibility of using the new experimental high-strength cold-resistant steel for manufacture of heavy-loaded constructions in machine-building, which are operated at low temperatures of Far North and Arctic region.

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