Study of phase and structural transformations in overcooled austenite for high-strength cold resistant steel during continuous cooling

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Essential part of strategic objects in oil/gas and machine-building complexes, transport industry and bridge building are operated in the conditions of simultaneous effect of low temperatures, static and dynamic loads as well as intensive wear. High-strength cold-resistance steels are considered as one of the materials, which can be used in such conditions. At present time, providing of principally new qualitative combination of properties of such steels is the actual scientific problem; the main parameters of these steels should be superior to the existing international analogues, they should present the unique combination of high strength, ductility as well as wear and cold resistance at the temperatures down to –70 °C. However, improvement of strength properties and hardness of rolled products leads to substantial decrease of cold resistance and ductility of steel; so, reaching of combination between high strength state and cold resistance is possible during definite structural and phase transformations, occurring in steels. Regularities of phase and structural transformations, occurring in high-strength cold-resistant steel with the following chemical composition (%, mass.): 0.15 C; 1.5 Mn; 0.20 Si; 1.7 (Ni+Cu); 0.035 (Ti+V+Nb); 0.0040 B during continuous cooling, were established in this research. Thermokinetic diagram of decomposition of overcooled austenite was built. It is shown, that steel with above-mentioned composition, which contains mainly if lathe martensite with small amount of bainite, is forming during continuous cooling with rate within the range 10-110 °C/c. Most part of martensite with lathe morphology can provide high strength of the researched steel, presence of dispersed structure of low-carbon bainite can provide high characteristics of resistance to brittle destruction, and hardness more than 350 HBW, which is achieved during cooling with rate more than 50 °C/c can provide high wear resistance.

Key words: high-strength cold-resistance steel, continuous cooling, phase transformations, structure, hardness, thermokinetic diagram.
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Introduction

At present time, essential part of the strategic objects in Russian oil/gas and machine-building complexes, transport industry and bridge building are operated in extremal conditions of simultaneous effect of low temperatures, static and dynamic loads as well as intensive wear. At the same time, providing of the conditions for mastering and sustainable development of the Arctic region is one of the priority tasks of the federal importance level. Arctic is considered as the object of territorial, resource and strategic interests of several countries which have influence on development of global economics and power engineering during the nearest decades [1-6].

Materials, that are used in the observed conditions, should have a combination of different parameters, which are usually hardly combined: high strength, ductility, toughness and weldability at low temperatures; it should be characterized by low sensitivity to stress concentrators and absence of sensitivity to brittle destruction. High-strength cold-resistant steel is one of materials that are intended for use in such conditions. However, parameters of steels presented in the global market meet the increased requirements mainly for only one of the key characteristics – either wear resistance, or cold resistance, or high strength etc. [7-10]. In this connection, providing of the principally new combination of properties in high-strength cold-resistance materials, is one of the actual scientific problems. Such combination includes [5, 6]:

- tensile strength not less than 1,200 MPa;
- yield strength not less than 950 MPa;
- relative elongation δ_5 not less than 10 %;
- HBW hardness not less than 350 (HV not less than 360);
- impact toughness KCV at the temperature -70 ºC not less than 30 J/cm^2.

Combination of the main parameters of the developed material is superior to the existing global analogues and presents the unique combination of high-strength, ductility as well as cold resistance at the temperature down to -70 ºC [11-13].

However, cold resistance and ductility of steel decreased substantially in the case of increase of strength properties and hardness of rolled products. Reaching of the combination of high-strength state with cold resistance is possible at certain structural and phase transformations occurring in steels.

The aim of this research is examination of the phase and structural transformations in undercooled austenite during continuous cooling of the developing high-strength cold-resistance steels.

Materials and methods of investigations

The research was carried out with laboratorial steel samples with the following chemical composition (%, mass., not more): 0.15 C; 1.5 Mn; 0.20 Si; 1.7 (Ni+Cu); 0.035 (Ti+V+Nb); 0.0040 B. The experiments for heating and cooling were conducted using the module Pocket Jaw of

Table 1. **Temperatures of phase transformations in the researched steel during continuous cooling**

Cooling rate, °C/s	Temperatures of phase transformations, °C					
	Ferrite extraction	Pearlite transformation		Bainite transformation		Martensite transformation
	Start	Start	Finish	Start	Finish	Start
1	834	695	656	656	469	-
10	704	-	-	610	465	465
50	-	-	-	624	460	460
70	-	-	-	640	462	462
100	-	-	-	622	465	465
110	-	-	-	-	-	463

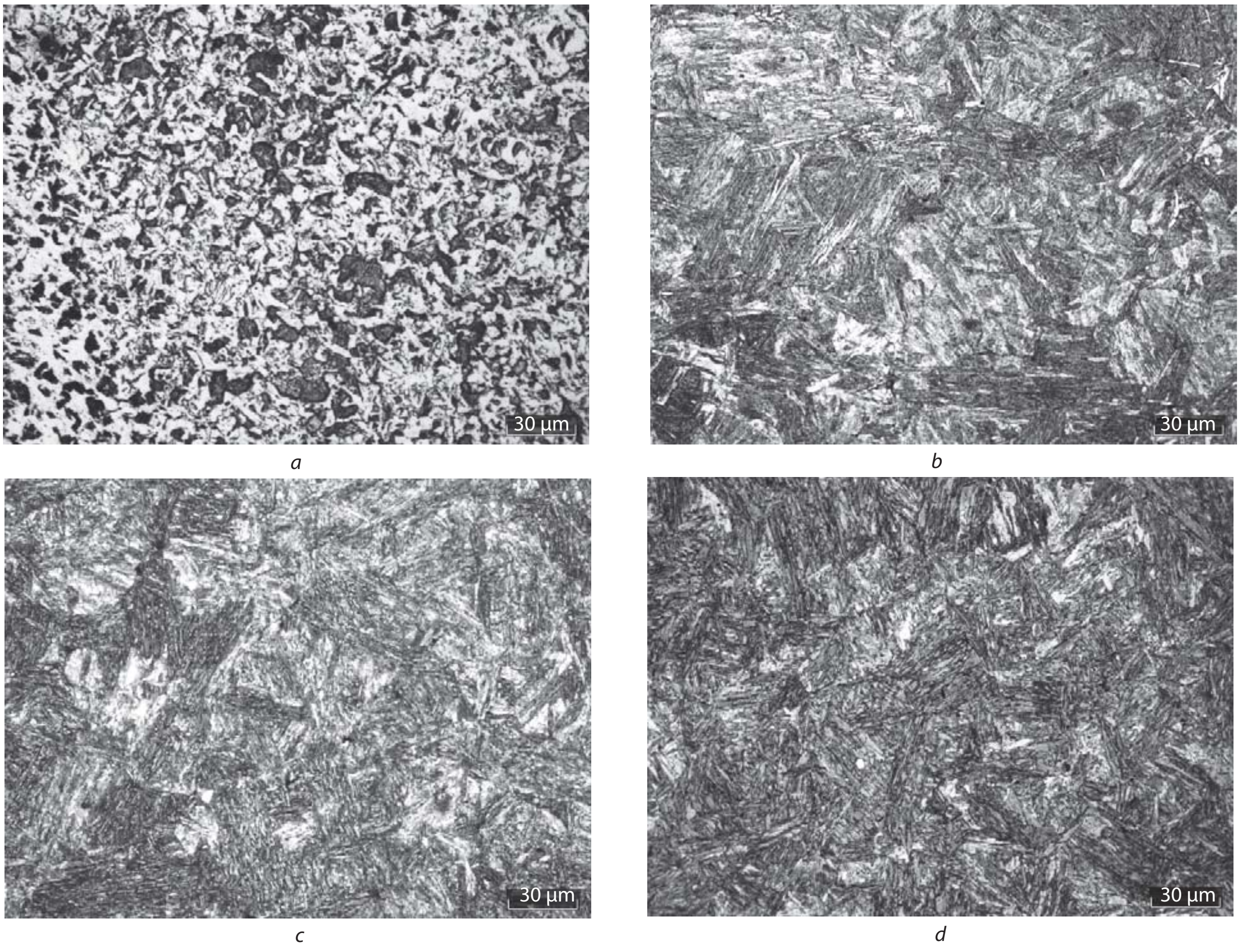


Fig. 1. Steel microstructure after cooling with rates: 1 (*a*), 10 (*b*), 50 (*c*) and 110 (*d*) °C/s, x 500

Gleeble 3500 complex, supplied by the system of dilatometric testing. The samples with diameter 10 mm were heated in vacuum to the temperature 930 °C, with reaching the austenite state. Consequent cooling was carried out with rates within the range 0.1-110 °C/c, which are realized in pilot-industrial conditions of manufacture of rolled products.

Metallographic examinations were conducted in the Centre of common use at "Nanosteels" Scientific and research institute of Nosov Magnitogorsk State Technical University. Polished sections for microanalysis were fabricated in the Buehler sample preparation line according to the standard technique. Light microscope Zeiss Axio Observer with the system of Thixomet PRO computer image analyzing system and scanning electron microscope (SEM) JSM 6490 LV were used for analysis of microstructure. Qualitative analysis was conducted using Thixomet PRO software complex on light and electron microscope images of microstructure. For this purpose, images were imported or introduced in Thixomet PRO system with assistance of digital video camera; then they were analyzed using specialized programs in the mode of manual measurements.

Vickers hardness was measured by Buchler Mikromet hardness meter via indentation of a diamond pyramid with the angle 136° between opposite planes, under load 1,000 kg and with loading duration 10 s.

Results of the research and discussion

Critical steel points were identified by bends on dilatometric curves, which were built within the coordinates " ΔD diameter variation – temperature", made: $A_{c1} \approx 707$°C, while $A_{c3} \approx 855$ °C. The temperatures of ferrite extraction from austenite, pearlite, bainite and martensite transformations during continuous cooling with rates within the range 0.1-110 °C/c were also identified by bends on dilatometric curves; they are presented in the **Table 1** [14, 15].

Microstructure, which was formed in the steel after cooling with different rates, is presented on the **Fig. 1**, while the results of qualitative analysis of microstructure and determination of hardness are displayed in the **Table 2**.

After cooling with the rate 1 °C/s, light grains of hypoeutectoid ferrite, dark areas of pearlite and gray areas that can't be identified via light microscopy are observed in the steel structure (Fig. 1*a*). The hardness value is 205 HV. At the cooling rate 10 °C/s, ferrite in the form of separate grains or islands is fixed, its amount in microstructure is small, while pearlite structure is not observed (Fig. 1*b*). In other words, diffusion pearlite transformation of overcooled austenite is not realized during continuous cooling within the noted range of rates. As soon as cooling rate rises from 10 to 110 °C/s, martensite is identified in the structure, its relative part increases (Fig. 1 *b*-*d*). Small amount of ferrite and appearance of martensite in the structure explains substantial increase of hardness to 324 HV for the cooling rate 10 °C/s. At the cooling rate 50 °C/s and higher, martensite component is mainly presented in microstructure (Fig. 1 *c*, *d*), hardness value increases and makes 438 HV for the cooling rate 110 °C/s.

To provide detailed identification of the structural components and to reveal the features of their morphology, the research via the SEM method was carried out; its results are shown of the **Fig. 2**. Analysis of the obtained data confirmed presence of polygonal ferrite and fine-dispersed pearlite in the structure after cooling with rate 1 °C/s. It also displayed that gray areas in microstructure are identified as granular bainite (in the amount about 15 %), containing of α-phase with martensite-austenite areas inside this phase (Fig. 2 *a*).

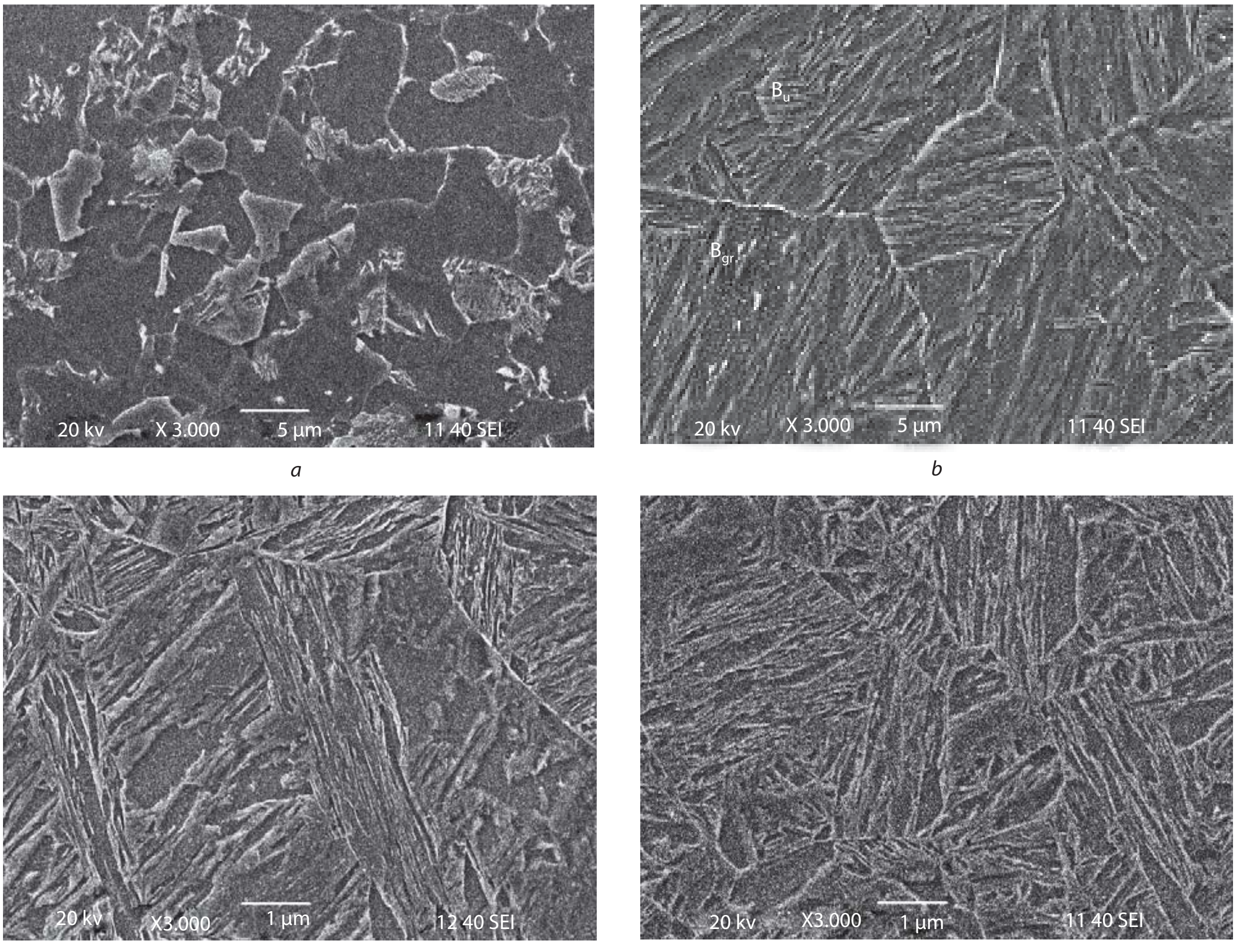
At the cooling rate 10 °C/s, microstructure is characterized by bainite component in the amount ~ 50 % and martensite with its volumetric part ~ 45 % (Fig. 2 *b*). Bainite component can be identified in its morphology to granular bainite (B_{gr}) and upper bainite (B_u), which consists of elongated α-phase lathes organized in packs with cementite that are located along boundaries of lathes.

When the cooling rate increases within the range 50-110 °C/s, bainite amount reduces from 35 to 5 % and martensite amount rises respectively from 65 to 95 % (Fig. 2 *c*, *d*), what is accompanied by further hardness increase. Bainite component in this case is characterized by morphology of upper bainite.

Based on the results of the complex dilatometric and metallographic analyses and hardness measurement, a structural diagram was built; it reflects the relationship between volumetric part of structural components and steel microhardness (from one side) and cooling rate (**Fig. 3**). Thermokinetic diagram (CCT) of decomposition of overcooled austenite for the steel with the follow-

Table 2. **Qualitative parameters of microstructure and microhardness of the researched steel after cooling with different rates**

Cooling rate, °C/s	Relative volumetric part of structural components, %				Hardness, HV
	Ferrite	Pearlite	Bainite	Martensite	
1	50	35	15	0	205
10	5	0	50	45	324
50	0	0	35	65	430
70	0	0	20	80	432
100	0	0	15	85	435
110	0	0	5	95	438



a *b*

c *d*

Fig. 2. Building features of the components of steel microstructure after cooling with rates:
1 (*a*), 10 (*b*), 50 (*c*) and 110 (*d*) °C/s, x 3000

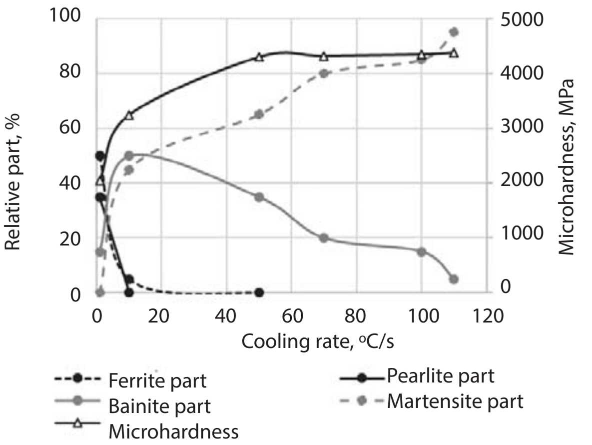


Fig. 3. Relationship between volumetric part of structural components and microhardness of the examined steel (from one side) and cooling rate

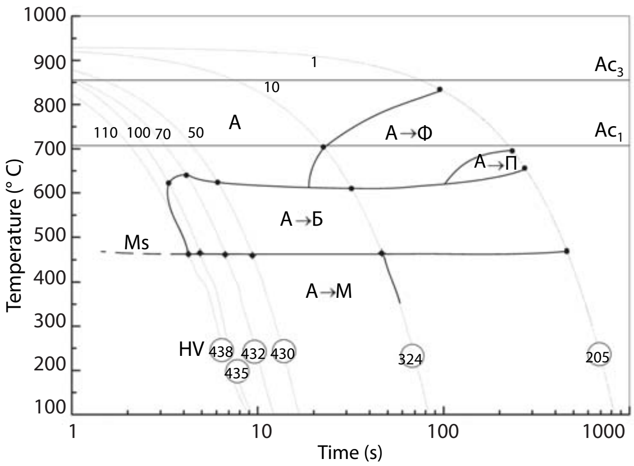


Fig. 4. Thermokinetic diagram of transformation of overcooled austenite in steel (A – austenite, Ф – ferrite, П – pearlite, Б –bainite, M – martensite, Ms – start of martensite transformation)

ing chemical composition (%, mass.): 0.15 C; 1.5 Mn; 0.20 Si; 1.7 (Ni+Cu); 0.035 (Ti+V+Nb); 0.0040 B was also built (**Fig. 4**). CCT analysis displayed that the higher critical cooling rate, which provides obtaining of martensite structure, is about 110 °C/s, while the critical rate, which provides obtaining of bainite-martensite structure is 110 °C/s.

High-strength cold-resistant steels should not only be characterized by high strength, but also guarantee durable and reliable operation in the conditions of increased wear and effect of impact loads, i.e. at the temperatures below zero. It is known, that wear resistance is mainly determined by steel microstructure. Combination of high values of hardness and low-temperature impact toughness can be provided after quenching and low tempering of quenching for martensite [16-20].

It was shown in several researches that non-tempered martensite is characterized by increased resistance against different kinds of wear, which is connected in the conditions of friction loading with development of the processes of dynamic ageing that can lead to efficient fixing of dislocations and intensive strengthening [19-23].

The most part of martensite with lathe morphology in the structure can provide high strength of the examined steel, while presence of dispersed structure of low-carbon bainite can provide high parameters of resistance to destruction [17-21].

Analysis of phase and structural transformations displayed that the examined steel with the following chemical composition (%, mass.): 0.15 C; 1.5 Mn; 0.20 Si; 1.7 (Ni+Cu); 0.035 (Ti+V+Nb); 0.0040 B should be cooled with the rate within the range 10-110 °C/s to obtain martensite-bainite structure, while hardness exceeding 360 HV can be achieved after cooling with the rate higher than 50 °C/s. Such cooling rates can be provided during water quenching.

Conclusion

Regularities of phase and structural transformations occurring in the high-strength cold-resistance steel with the following chemical composition (%, mass.): 0.15 C; 1.5 Mn; 0.20 Si; 1.7 (Ni+Cu); 0.035 (Ti+V+Nb); 0.0040 B during continuous cooling were established; thermokinetic diagram of decomposition of undercooled austenite was built.

It is shown that the structure consisting mainly of lathe martensite with small amount of bainite is forming in the steel with above-noted chemical composition during continuous cooling with the rate within the range 10-110 °C/s. In this case, the most part of martensite with lathe morphology in the structure provides high strength of the examined steel, while presence of dispersed structure of low-carbon bainite provides high resistance to destruction. Hardness values exceeding 360 HV are achieved via cooling with the rate higher than 50 °C/s.

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