ISSN 2075-1133, Inorganic Materials: Applied Research, 2019, Vol. 10, No. 6, pp. 1265–1281. © Pleiades Publishing, Ltd., 2019.
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METAL SCIENCES. METALLURGY

Scientific and Technological Bases for Developing Cold-Resistant Steel with a Guaranteed Yield Strength of 315–750 MPa for Arctic Conditions. Part 1: Alloying Principles and Requirements for Sheet Product Structure

O. V. Sych*

National Research Center Kurchatov Institute—Central Research Institute of Structural Materials Prometey, St. Petersburg, 191015 Russia

**e-mail: mail@crism.ru*

Received August 14, 2018

Abstract—The results obtained upon choosing rational alloying and microalloying for cold-resistant steels with a guaranteed yield strength of 315–750 MPa on the basis of established interrelations between phase transformations, structure, mechanical properties, serviceability parameters, and the content of main alloying elements are presented. Quantitative requirements for various structural parameters and their maximum permissible difference throughout sheet product thickness up to 100 mm have been developed, depending on the strength category and manufacturing technology (thermomechanical treatment with accelerated cooling, quenching from separate furnace heating or rolling heating with high temperature tempering) to provide guaranteed characteristics of strength, cold resistance (impact energy *KV* at a testing temperature from –60 to –80°C, critical ductile-to-brittle transition temperature T_{kb}, and nil ductility temperature NDT), and crack resistance according to the criterion of critical crack tip opening displacement (CTOD).

Keywords: low-alloy steel, economically alloyed steel, Arc index, thermomechanical treatment, quenching, quenching from rolling heating, tempering, mechanical properties, cold resistance, serviceability, crack resistance, structure parameters, ferrite, bainite, martensite

DOI: 10.1134/S207511331906025X

INTRODUCTION

The large-scale development of hydrocarbon resources of the offshore Arctic shelf and coastal zone, an intensive year-round exploitation of the Northern Sea Route, and the development of the coastline of the Arctic area require the use of highly reliable cold-resistant steels to create technical facilities for the production, transport, storage, and shipment of hydrocarbons taken from offshore fields, such as novel icebreakers of increased capacity, ice-resistant platforms, loading terminals, marine ice-resistant terminals, crane and crane-assemblage ships with heavy lifting capacity, hoisting and transport equipment, alternative power engineering, and other marine and engineering equipment. For a number of structures, sheet products up to 100 mm thick are required.

The steels used for the construction of such structures are subject to a number of special requirements. This is a wide range of strength characteristics in combination with a high level of viscoplastic properties, high resistance with respect to brittle fracture and extended viscous fracture at working temperatures ranging from –40 to –60°C, resistance with respect to static, dynamic and cyclic loads, no corrosion-mechanical damage in the course of the calculated operating lifetime, resistance with respect to layered fractures in the assemblies of welded structures, sufficient manufacturability of production and welding under low-temperature conditions. Corrosive environments, high specific loads, cyclic loading, low temperatures, and a number of requirements including those of an economic nature determine the search for new approaches to the development of structural steels intended for use in the Arctic.

To date, novel low-cost technologies for manufacturing sheet products with a thickness up to 40–60 mm based on structural low-carbon steels for shipbuilding and pipeline transport have been developed, including with the participation of the author. These technologies consist in thermomechanical treatment with accelerated cooling (TMCP + AC) for low-alloy steels with yield strength of 315, 355, 390, 420, and 460 MPa and quenching after a separate furnace or rolling heating and further tempering (Q + T or Q_{rh} + T) for alloyed steels with normalized yield strength amounting to 500 MPa and more.

The most important problems consist in increasing in the metallurgical quality of steel via eliminating the segregation of hazardous impurities and nonmetallic inclusions and in providing the formation of a quasi-isotropic structure throughout the thickness of a rolled sheet for its fineness at all the scale levels (up to 200–500 nm). The authors of [1, 2] have formulated the principles for developing a quasi-isotropic structure that consist in eliminating the formation of extended phase boundaries and in the formation of morphologically similar structural components having close grain and subgrain size, dislocation density, carbide phase dispersion and morphology. This problem can be solved via choosing a chemical composition that makes it possible to vary the rates of cooling in a rather wide range with no change in the nature of phase transitions (important for plate rolling) and sequentially making the structure finer at each stage of the technological process.

The creation of a quasi-isotropic structure throughout the thickness (up to 60 mm) of sheet products makes it possible to maintain high viscoplastic properties while improving the strength characteristics of structural steel [1–3]. On the basis of this approach, a series of pipe and shipbuilding steels has been developed. The Prirazlomnaya offshore ice-resistant platform and the Arctic drilling platform for operation in the Arctic latitudes have been constructed using such materials; the pipes made of such materials have been used for the construction of the Bovanenkovo-Ukhta gas pipeline.

However, this direction is still far from exhausted; more and more powerful means for intense plastic deformation are being commissioned in Russia, and technological methods for thermal deformational impact at various stages of rolling are under improvement [4–7].

At the current stage, the most significant issues from the standpoint of providing the construction of novel marine equipment with economical materials of an expanded assortment (up to 100 mm thick) are a guaranteed provision of serviceability parameters for shipbuilding steels having various strengths while reducing their production cost. More than 15 years of experience in the production of shipbuilding steels with the use of thermomechanical treatment since the beginning of the 2000s has shown that often (upon obtaining suitably commissionable mechanical properties), it is not possible to obtain satisfactory serviceability parameters in the course of certification testing (according to the ductile-to-brittle transition temperature T_{kb}[1] for large samples, nil ductility temperature NDT[2], and critical crack tip opening displacement CTOD [8]) taking into account a preset operating temperature.

These tests were previously conducted in the course of certification in order to expand the possibilities of using the developed materials for the most critical structural elements, according to the requirements of the Russian Maritime Register of Shipping (RMRS).

In 2012, the RMRS was supplemented with requirements for steels with the Arc index. According to the 2017 edition of the RMRS "Rules for the Classification and Construction of Ships," "Arc" is a symbol added to the designation of a steel grade for which a set of tests has been performed according to the RMRS program to determine additional cold and crack resistance characteristics that meet the requirements for steels with improved weldability. Next to the Arc index, an estimated (minimum) material operating temperature T_d is indicated (without a minus sign) at which the steel can be used for manufacturing any structural elements with no restrictions.

The fundamental difference between steels with the Arc index and category F steels consists in the fact that the serviceability parameters of sheet products and welded joints made of such steels should be guaranteed by the production technology thereof. New requirements for steels with the additional index "Arc" are reflected in the National RF Standard GOST R 52927-2015. However, to date, such technologies have not been available at Russian plants.

In this regard, the purpose of this work, carried out partly in the scope of the Arctic Steel project, consisted in developing scientifically justified approaches to the choice of rational alloying and microalloying for low-carbon low-alloy and economically alloyed cold-resistant steels, including those with the Arc index, with a yield strength of 315–750 MPa and to the formulation of comprehensive quantitative requirements for the structural parameters of sheet products up to 100 mm thick, to provide a decrease in the anisotropy of mechanical properties and obtain guaranteed serviceability in the low-temperature range from –40 to –60°C.

MATERIALS AND METHODS

As the material for the investigation, we chose sheet products 25–100 mm thick made of low-carbon low-alloy and economically alloyed cold-resistant steels, whose chemical composition is presented in Table 1.

The sheet products under study were distinguished by the type of initial workpiece (a converter slab or ingot melted in an electric furnace), by the manufacturing technology—thermomechanical treatment with accelerated cooling (TMCP + AC), quenching from rolling or separate furnace heating with high-temperature tempering (Q_{rh} + T or Q + T), and by the alloying level depending on the strength category (Table 2).

The requirements for the results of the stretching and impact bending tests of sheet products made of

[1] T_{kb} is the critical temperature of brittleness at which at least 70% of a fibrous component is observed in the break of a full-thickness sample with a concentrator in the form of a notch under a three-point static bend to fracture.

[2] NDT is the critical temperature of brittleness ("nil ductility temperature") defined as the maximum temperature at which a breakage of a standard-sized sample with brittle cladding and a crack-initiating notch under impact loading occurs.

Table 1. Chemical composition of low-carbon low-alloy and economically alloyed steels, wt %

Strength category, MPa	C	Si	Mn	P	S	Cr	Ni	Cu
315–390	0.05–0.10	0.19–0.27	0.75–1.35	0.004–0.010	0.001–0.006	–	0.02–0.69	0.02–0.25
420–460	0.06–0.09	0.20–0.25	1.25–1.65	0.007–0.010	0.001–0.004	0.04–0.18	0.20–0.85	0.12–0.40
500–620	0.08–0.10	0.22–0.28	0.60–0.66	0.006–0.010	0.002–0.003	0.48–1.16	1.35–2.02	0.36–0.54
690–750	0.07–0.09	0.25–0.33	0.65–1.92	0.005–0.007	0.002–0.005	0.49–0.83	0.45–2.18	0.23–0.68
	Al	N	Ti	Mo	Nb	V	C_{eq}* [1]	P_{cm}** [2]
315–390	0.025–0.06	0.005–0.008	–	0.001–0.07	0.022–0.041	0.002–0.057	0.21–0.40	0.11–0.20
420–460	0.023–0.040	0.005–0.008	0.002–0.014	0.01–0.20	0.002–0.05	0.002–0.028	0.32–0.46	0.16–0.22
500–620	0.020–0.039	0.005–0.008	–	0.12–0.24	0.02–0.03	–	0.45–0.61	0.21–0.25
690–750	0.012–0.036	0.005–0.009	0.003–0.015	0.24–0.35	0.024–0.052	–	0.50–0.60	0.23–0.25

* C_{eq} = C + (Mo + Cr + V)/5 + (Cu + Ni)/15 + Mn/6, wt %.
** P_{cm} = C + (Mo + Cr + Cu)/20 + Si/30 + Ni/60 + Mo/15 + V/10, wt %.

Table 2. Production technology of sheet products under investigation

Strength category MPa	Maximum thickness of rolled products, mm	Initial workpiece	Manufacturing technology
315–390	100	Slab, ingot	TMCP + AC
420–460	60		
	100	Slab	Q_{rh} + T
500	60	Slab, ingot	TMCP + AC, Q + T, Q_{rh} + T
620	50		Q + T, Q_{rh} + T
690	50		
750	40	Ingot	

cold-resistant steels with strength categories of 315–750 MPa are shown in Table 3.

Additional requirements for cold resistance parameters for critical temperatures T_{kb} and NDT are presented in Table 4.

The requirements for crack resistance according to the criterion of critical crack tip opening displacement (CTOD) at temperature T_d for the base metal (BM) and the metal of the heat-affected zone (HAZ) are presented in Table 5 (T_d is the minimum calculated working temperature up to which the steel can be used for making any structural elements with no restrictions).

On the basis of the results of testing for the serviceability of the base metal and welded joints, the highest temperature T_d (being not lower than the temperature value at which steel and its welded joints can be operated with no restrictions) that meets all the specified criteria is determined.

The mechanical tests were carried out in accordance with the requirements of GOST R 52927-2015. The value of ductile-to-brittle transition temperature T_{kb} was determined in accordance with the requirements of the RMRS rules, and the value of nil ductility temperature NDT was determined in accordance with the requirements of the RMRS rules and ASTM E208. The CTOD fracture toughness testing was carried out in accordance with the requirements of the standards of the RMRS rules and BS 7448 p.1, BS/EN/ISO 15653, and ISO 12135.

The structure parameters were studied by means of optical metallography using an Axio Observer A1M microscope with a digital image analyzer for thin metallographic sections after etching in a 3% alcohol solution, as well as by means of automatic analysis of electron backscattering diffraction patterns (EBSD analysis) using a Quanta 3D FEG scanning electron

Table 3. Requirements for strength and viscoplastic properties of sheet products

Steel grade	Yield strength, MPa, not lower than	Tensile strength, MPa	Relative elongation, not lower than, %	Impact energy *KV*, J, at –20, –40, –60°C (for categories D, E, and F respectively), including after mechanical aging, not lower than
(D, E) F32W^{Arc}	315	440–570	22	50
(D, E) F36W^{Arc}	355	490–630	21	
(D, E) F40W^{Arc}	390	510–660	20	
(D, E) F420W^{Arc}	420	530–680	18	80
(D, E) F460W^{Arc}	460	570–720	17	
(D, E) F500W^{Arc}	500	610–770	16	
(D, E) F620W^{Arc}	620	720–890	15	
(D, E) F690W^{Arc}	690	770–940	15	
(D, E) F750W^{Arc}	750	800–970	15	

Table 4. Requirements for critical temperatures T_{kb} and NDT inherent in steels with Arc index

Rolled product thickness, mm	NDT, °C					T_{kb}, °C				
	Arc20	Arc30	Arc40	Arc50	Arc60	Arc20	Arc30	Arc40	Arc50	Arc60
25–30	–35	–45	–55	–65	–75	–20	–30	–40	–50	–60
31–40	–40	–50	–60	–70	–80	–5	–15	–25	–35	–45
41–50	–45	–55	–65	–75	–85	+5	–5	–15	–25	–35
51–60	–50	–60	–70	–80	–90	+5	0	–10	–20	–30
More than 60	–50	–60	–70	–80	–90	+5	0	–5	–10	–15

microscope. The value of structure anisotropy coefficient K_a was determined using a Thixomet image analyzer together with the St. Petersburg Polytechnic University [9, 10]. The fine structure studies were performed using a Tecnai G2 30 S-TWIN transmission electron microscope (TEM) at an accelerating voltage of 120 kV.

THE PRINCIPLES OF ALLOYING AND THE DEVELOPMENT OF REQUIREMENTS FOR STRUCTURE THROUGHOUT THE THICKNESS OF SHEET PRODUCTS UP TO 100 mm THICK BASED ON COLD-RESISTANT STEELS FOR THE ARCTIC

The metallurgical approaches to the development of cold-resistant structural steels are based on the interrelations between alloying, phase transformation kinetics, thermal deformation modes of hot plastic deformation, the parameters of accelerated cooling, quenching, high-temperature tempering, and the structure under formation, mechanical properties, and serviceability parameters that have been studied in sufficient detail within the last 10–15 years. Specialists at the Central Research Institute of Structural Materials Prometey (since 1947 as a branch institute of shipbuilding) and the Bardin Central Research Institute of Ferrous Metallurgy, the Baykov Institute of Metallurgy and Materials Science of the Russian Academy of Sciences, and some other teams dealt with these problems As a result, principles for alloying and technologies for manufacturing sheet products based on shipbuilding cold-resistant steels (strength categories of 315–690 MPa up to 70 mm thick [1, 2]) and pipe cold-resistant steels (with a yield strength of at least 500–690 MPa [3] up to 35 mm thick) were proposed, which provide the formation of the quasi-homogeneous structure with the required dispersion and morphology throughout the thickness of the rolled product.

However, to date, quantitative requirements neither for the characteristics of the structure anisotropy throughout sheet thickness (except for approaches to restricting the size and volume fraction of lath bainite areas in pipe steels [3]) nor for the structural parame-

Table 5. Requirements for CTOD values for BM and HAZ inherent in steels with Arc index

Rolled product thickness, mm	CTOD, mm, at T_d, not lower than									
	BM					HAZ				
	F32W; F36W	F40W; F420W	F460W; F500W	F620W	F690W	F32W; F36W	F40W; F420 W	F460W; F500W	F620W	F690W
25–30	0.15	0.15	0.20	0.20	0.25	0.10	0.10	0.10	0.15	0.20
31–35	0.15	0.15	0.20	0.20	0.25	0.10	0.15	0.15	0.20	0.25
36–50	0.20	0.20	0.25	0.25	0.30	0.10	0.15	0.15	0.20	0.25
51–70	0.20	0.25	0.30	0.30	0.35	0.15	0.20	0.20	0.25	0.30
More than 70	0.25	0.25	0.30	0.35	0.35	0.15	0.20	0.20	0.25	0.30

ters of steels (except for grain size, an approximate relationship between structural components, the density of dislocations and the size of carbide phases for shipbuilding low-alloy and alloyed steels [1, 2, 11, 12]) have been established, despite quite an extensive experience in manufacturing sheet products at Russian industrial enterprises. No issues concerning a comprehensive quantitative assessment of structural changes throughout the thickness of sheet products were considered. There is no experience in manufacturing sheet products with a thickness of 71–100 mm from low-alloy steels with the use of TMCP + AC and Q_{rh} + T technologies.

In recent years, novel methods have been proposed for making the structure fine via improving the temperature-deformation rolling schemes [4–7] with more exacting requirements for the organization and monitoring of technological process parameters. However, these methods require scientifically based adjustment of the content of main alloying and microalloying elements [13–16].

The studies performed by the author have shown that, upon two-stage hot plastic deformation in low-alloy and economically alloyed steels, even seemingly insignificant technological affects and chemical composition variations in narrow ranges (within 0.20%) can lead to a significant change in the morphological and crystallographic parameters of the structure (and, as a result, mechanical properties and serviceability of sheet products) while maintaining the phase composition. Evaluating the contribution of various parameters to the formation of the structure has become possible owing to the development of novel methods for recognizing and quantifying the grain and subgrain structure of structural components [9, 10, 17, 18, 38].

Choosing Rational Alloying and Microalloying of Cold-Resistant Steels with Guaranteed Serviceability Parameters

The choice of a combination of alloying elements for shipbuilding steels of various strength categories is based on the current trend of reducing the alloying level and the implementation of the principle of chemical composition unification. As shown by studies carried out under the guidance and with the direct participation of the author, concerning the effect of carbon and the main alloying elements (manganese, nickel, chromium, copper, and molybdenum) exerted on phase and structural transformations, hardenability of steel, strength and plastic properties, impact energy at low temperatures, the ductile-to-brittle transition temperature T_{kb} and nil ductility temperature NDT, crack resistance CTOD, and, of course, weldability and corrosion-mechanical strength for low-alloy and economically alloyed steels with a guaranteed serviceability, including with the Arc index, additional requirements should be established from the standpoint of their alloying and microalloying.

Low-Alloy Steels with Yield Strength Not Less than 315–460 MPa

For manufacturing sheet products based on low-alloy shipbuilding and pipe cold-resistant steels using thermomechanical treatment, a manganese-nickel alloying composition with small additions of copper, chromium, and molybdenum is traditionally used. At the same time, pipe steels are very economically alloyed owing to the enormous metal consumption in the main pipelines: at a higher manganese content (up to 1.8–2.0%), the addition of expensive alloying elements (nickel, copper, chromium, and molybdenum) is significantly reduced, whereas the content of microalloying elements exerting an inhibitory effect on recrystallization processes is increased, causing their incomplete course.

As the practice of manufacturing pipe steels (up to 35 mm thick) shows, not all the requirements for shipbuilding steels can be provided for such chemical compositions with increasing sheet product thickness. This primarily concerns the type of break for a large-sized technological sample—one of the main tests of sheet products for shipbuilding that characterizes the uniformity of the structure throughout the thickness. In addition, significant slivers are exhibited in pipe

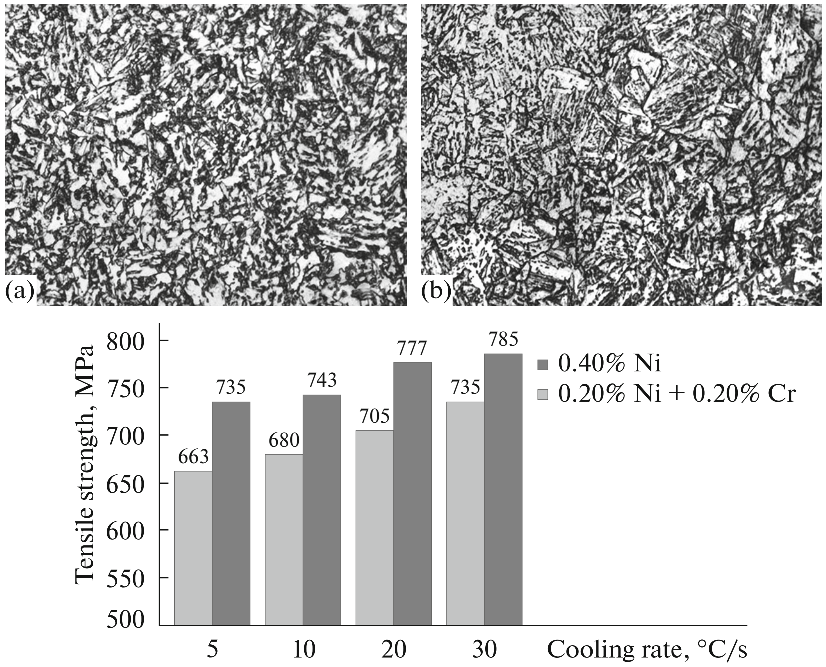

Fig. 1. Effect of adding ferrite-forming elements under simultaneous decrease in the content of elements that stabilize austenite exerted (a, b) on the structure and (c) on the strength of low-alloy steel.

steel breaks, which often even improve the assessing results with respect to a fraction of viscous component in the breaks of samples after dynamic testing with a falling load (drop weigh tear test, DWTT) and testing for static bending with the determination of ductile-to-brittle transition temperature T_{kb}, but are unacceptable for shipbuilding steels, which is regulated by the RMRS rules.

For slivers to occur in the viscous fracture area, it is necessary that the size of the structural inhomogeneity determining the layered structure be at least (0.1–0.2) with respect to the size of the zone of action of high stresses in the Z direction. In the case of a viscous fracture mechanism, the critical crack tip opening displacement (CTOD) amounts to 150–200 μm; therefore, it should be expected that structural inhomogeneities larger than 100 μm in size could lead to the formation of delaminations in the course of fracture [19, 20]. Such structural inhomogeneities include, first of all, extended areas of lath bainite formed within the former unrecrystallized austenitic grains elongated in the rolling direction.

The authors of [4, 13] have proposed a technological method for the fragmentation of the initial unrecrystallized austenitic grain aimed at intensifying the ferrite transformation combined with the formation of a granular bainite structure.

The main idea consists in an additional alloying of pipe steel having a guaranteed yield strength amounting to 500 MPa by ferrite-forming elements, in particular, chromium, in microalloying with vanadium upon simultaneously reducing the content of elements stabilizing austenite, such as nickel and copper. In this case, it is necessary to create certain temperature-deformation conditions that provide controlled carbon binding leading to an increase in critical conversion points Ar_3 and Ar_1 and to the formation of granular structures having a high ductility and viscosity in the cooling range of 5–30°C/s used in the industrial treatment of sheet products. In combination with chromium, this leads to an increase in the fraction of quasipolygonal ferrite (Fig. 1a).

Under steel alloying with the elements that cause increasing hardenability (nickel, copper, and molybdenum) and at a rather high manganese content amounting to ~1.65% and at a cooling rate of 5–30°C/s, a bainitic structure is formed, wherein lath bainite prevails (Fig. 1b). The author has found that the replacement of 0.4% Ni by (0.2% Ni + 0.2% Cr) leads to a decrease in the strength characteristics of steel by 50–70 MPa (Fig. 1c).

Industrial testing of the nickel-chromium composition of pipe steel [13] for manufacturing shipbuilding sheet products for lower strength categories 420–460 MPa [5] has shown that, in the case of high cold resistance parameters (the impact energy being not less than 200 J up to a testing temperature of –80°C , ductile-to-brittle transition temperature T_{kb} = –15 to –20°C, and nil ductility temperature NDT = –75 to –80°C for 50-mm-thick sheet products), the values of critical crack tip opening displacement CTOD required for steels with the Arc40 index at test temperature of –40°C

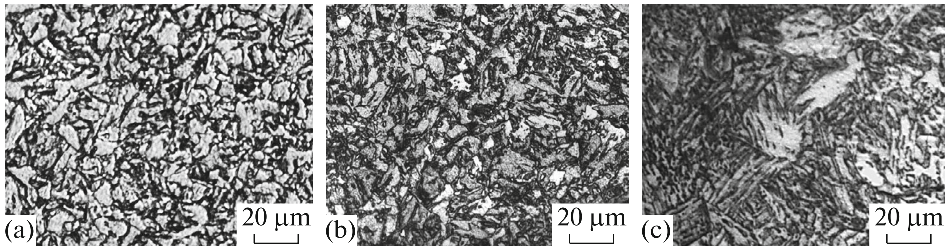

Fig. 2. Structure of low-alloy steel (a) with C_{eq} = 0.26%, (b) with C_{eq} = 0.38%, and (c) with C_{eq} = 0.44% after cooling at a rate of 5°C/s.

are provided only up to a rolled product thickness of 40 mm (the average CTOD value is closer to the lower limit of 0.27 mm, while the required value should be at least 0.20–25 mm).

Comprehensive studies on phase and structural transformations in low-alloy shipbuilding steels with a carbon equivalent of C_{eq} = 0.21–0.46% (owing to change in the content of carbon and main alloying elements, i.e., manganese, nickel, copper, and molybdenum) have shown that, over the entire range of cooling rates (from 5 to 30°C/s, which is typical for cooling of the surface and the average thickness of sheet products of 100 mm under industrial conditions), it is possible to provide the formation of a ferrite-pearlite-bainitic structure with at C_{eq}= 0.21–0.25% (for steel with a strength category of 315 MPa) and of a ferrite-bainitic structure at C_{eq} = 0.26–0.40% (for steels with strength categories of 355–460 MPa). With increasing C_{eq}, the fraction of ferrite decreases with a simultaneous increase in the content of the bainitic component (Figs. 2a, 2b), which provides the required strength of steel.

Upon increasing C_{eq} to 0.41–0.46%, a bainitic or bainite-martensitic structure involving bainite of different morphology is formed at cooling rates of at least 5°C/s (Fig. 2c) with the required hardenability throughout the entire cross section of sheets of large thickness made of low-alloy steel in the case of using Q_{rh} + T and Q + T. For such steels, it is worthwhile to perform microalloying with vanadium owing to the effect of dispersion hardening [21, 22] upon tempering low-alloy steel with a bainitic structure of a granular type and a developed substructure (after two-stage thermodeformation processing), for which the introduction of 0.03% of vanadium leads to a 40–50 MPa increase in strength.

In choosing rational alloying and microalloying for cold-resistant steels to work in the Arctic, the main problem is still to provide the stability of strength characteristics in combination with high values of impact energy throughout the thickness of sheet products and serviceability parameters at low temperatures.

The statistical analysis of mechanical properties carried out for 70–120 sheets with a thickness of 40–60 mm made of steel with different content of carbon and the main alloying elements (manganese, nickel, copper) with a yield strength of at least 315–460 MPa belonging to cold resistance categories E and F manufactured under industrial conditions according to TMCP + AC technology has shown the following.

The majority of compositions exhibit a high average value of impact energy at testing temperatures of –40 and –60°C throughout the thickness of sheet products; however, in rare cases, decreases are observed that do not meet the requirements of the RMRS rules and GOST R 52927-2015 (Table 6).

Low-carbon steel with composition 1 (0.08–0.10% C) containing Mn in the amount of 1.35–1.50% with no additional alloying by other elements, microalloyed with V + Nb, at a high strength level (at a level of strength categories 420–460 MPa) does not provide the required value of cold resistance for sheet products; there is a significant variation in the values of impact energy in the middle of the sheet thickness even at a testing temperature of –40°C (Table 6).

Under a 0.50–0.60% decrease in Mn content with additional alloying with Ni in the range 0.15–0.20%, it is possible to provide in steel having composition 2 a stable combination of strength parameters and impact energy throughout the thickness of sheet products with strength category 315 MPa (Fig. 3a) A 0.40% increase in the Mn content in steel with composition 3 promotes an increase in strength characteristics by 50–60 MPa as compared with composition 2 (Fig. 3a), which provides the requirements for steels with strength categories 355–390 MPa under simultaneous reduction of the average values of impact energy by 70–80 J and the stability of their values.

An 0.50% increase in the Ni content in steel having composition 4 leads to a significant increase in strength characteristics (by 75–80 MPa) according to their average values (Fig. 3 b), satisfying strength categories 420–460 MPa; however, in combination with an increased carbon content amounting to 0.08–0.10%, such a change in chemical composition is unfavorable from the standpoint of the impact energy stability, especially in the middle of sheet product thickness (more than 50% of the values are below 50 J).

A 0.03% decrease in the carbon content in low-alloy steel (composition 4 as compared to composition 6)

Table 6. Effect of C, Mn, Ni, and Cu content on the impact energy stability in the testing temperature range from –40 to –60°C

Composition number	Carbon content, %	Average content of main alloying elements	Impact energy *K*V, J, in the temperature range from –40 to –60°C*		Unsatisfactory result in the impact energy in the temperature range from –40 to –60°C, %*	
			surface	middle	surface	middle
1	0.08–0.10	1.4% Mn	218*	126*	0	28
2		0.8% Mn + 0.2%Ni	294*	291*	0	0
3		1.2% Mn + 0.2%Ni	226*	207*	4	8
4		1.2% Mn + 0.7%Ni	219	78	8	55
5		1.2% Mn + 0.8% Ni + 0.4%Cu	149	129	19	36
6	0.05–0.07	1.2% Mn + 0.7%Ni	261	201	2	13
7		1.2%Mn + 0.7% Ni + 0.2%Cu	222	199	0	7
8		1.4%Mn + 0.5%Ni + 0.2%Cu	276	224	0	4

* Impact bending tests were carried out at a temperature of –40°C.

does not cause any significant decrease in strength characteristics (by less than 15–25 MPa), but it causes an increase in the cold resistance of steel (in particular, the average value of impact energy KV^{-60} in the middle of the sheet thickness exhibits an increase by about 120 J, whereas the stability of its values exhibits an approximately fourfold increase).

The additional alloying of steel having composition 7 with copper in small amounts (0.15–0.20%) helps to reduce the dispersion of the values of tensile strength. However, it has been found that the introduction of copper in an amount of 0.35–0.40% into steel having composition 5 containing 0.70–0.85% of Ni provides the highest strength level with unstable results of impact bending tests at a temperature of –60°C throughout the thickness of sheet products (Fig. 3c). To increase the stability of strength characteristics and impact energy at low test temperatures, for sheet products with a thickness greater that 40 mm, the most efficient procedure consists in replacing a part of Ni by Cu (not more than 0.20%), as demonstrated for steel with composition 8 (Fig. 3c).

In the case of such complex alloying with Ni and Cu and restricting their content within narrow limits, the control of strength characteristics for strength categories from 355 to 460 MPa is possible owing to the variation of manganese content from 1.15 to 1.50%.

Figure 4 shows the minimum values of ductile-to-brittle transition temperature T_{kb} and nil ductility temperature NDT according to a statistical analysis performed for low-alloy shipbuilding steels with different content of the main alloying elements—Mn, Ni, and Cu.

Low-alloy steels containing Mn in an amount of 1.35–1.40% without Ni and Cu do not meet the requirements for the main cold resistance parameter, i.e., temperature T_{kb}, even at a sheet thickness of 25–

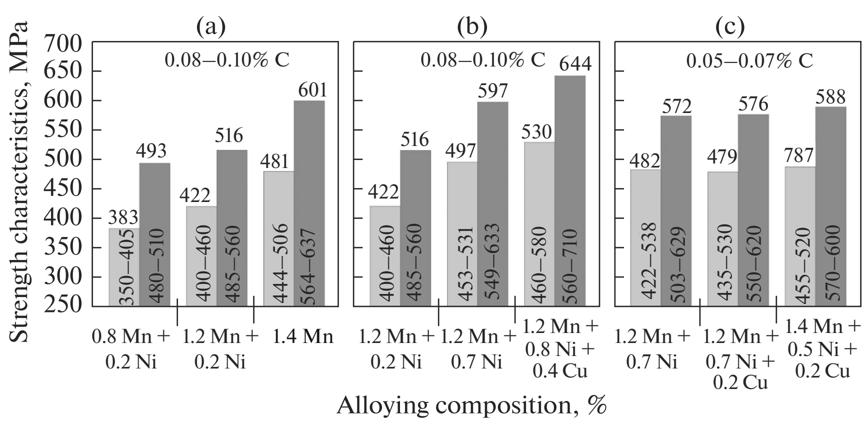

Fig. 3. Effect of the content of carbon and main alloying elements exerted on the level of strength characteristics of sheet products: (a) Mn, (b, c) Ni and Cu ((▫) $Rt_{0.2}$; (▪) Rm).

30 mm (Fig. 4a), which depends on the level of structure uniformity and isotropy throughout the thickness of sheet products. This is connected with the formation of an anisotropic ferrite-bainitic structure in the middle of the sheet thickness having large lath bainite areas with a ferritic fringe along their boundaries. A value of NDT temperature that is less sensitive (among all the determined serviceability parameters) with respect to the structure heterogeneity throughout the thickness of rolled products can be provided at the lower limit of the requirements for the thickness of the rolled sheet not more than 40 mm.

The requirements for temperature NDT can be provided via alloying steel jointly with Mn, Ni, and Cu (Fig. 4b). In this case, in the entire range of considered sheet product thicknesses amounting to 30–60 mm, the achievement of specified cold resistance characteristics (T_{kb} and NDT), as well as a high crack resistance according to the criterion of critical crack tip opening displacement(CTOD) in the temperature range from –40 to –60°C, is provided in Mn-alloyed steel, with a total content of (Ni + Cu) lower than 1.0%.

Increasing total (Ni + Cu) content to 1.0–1.2% leads to obtaining required temperature values T_{kb} in a limited range of sheet product thicknesses (up to 40 mm). For a greater thickness, the minimum values of T_{kb} exhibit an increase to a temperature ranging from –5 to 5°C, and, at the same time, the stability of the steel crack resistance parameter worsens (the value of testing temperature at which the requirements corresponding to CTOD are met exhibits an increase to the range from –20 to –30°C).

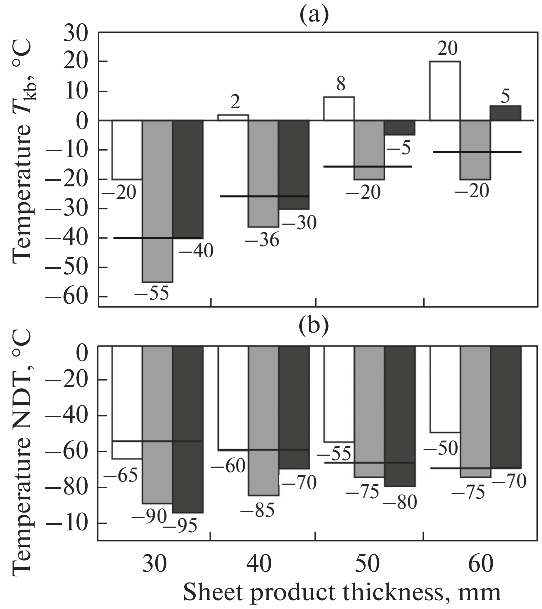

Fig. 4. Minimum critical temperature (a) of ductile-to-brittle transition T_{kb} and (b) of nil ductility NDT for sheet products 30–60 mm thick based on low-alloy steels with different content of main alloying elements (lines correspond to the level of STD requirements): (□) (1.35–1.40)% Mn without Ni and Cu; (▩) (1.15–1.20)% Mn + (0.85–0.90)% (Ni + Cu); (■) 1.15–1.20)% Mn + (1.15–1.20)% (Ni + Cu).

Economically Alloyed Steels with Yield Strength Not Less than 500–750 MPa

It is much more difficult to maintain a complex of good mechanical properties and serviceability parameters in the case of the economical alloying of steels with higher strength categories of 500–750 MPa. This is connected with the fact that the chosen ranges of main alloying elements for high-strength steel (manganese, nickel, copper, chromium, and molybdenum) under the restriction of carbon equivalent C_{eq}, in order to increase cold resistance and weldability should provide a required hardenability value throughout the entire rolled sheet thickness amounting to 50–60 mm.

The chemical composition of steel should guarantee the formation of a bainitic, bainite-martensitic, or martensitic structure (in the absence of a ferritic component) in the range of cooling rates from 50 to 5°C/s, typical for cooling the surface layers and the middle of the sheets up to 50–60 mm thick under quenching starting the rolling heating or separate furnace heating in an industrial environment.

Earlier [23], it was shown that it is possible in principle to reduce the content of expensive alloying elements (Ni, Cr, and Cu) by 20–30% as compared with traditional compositions for manufacturing sheet products belonging to strength categories of 500–690 MPa. In particular, for steel with a guaranteed yield strength of 690 MPa, a chemical composition has been proposed with C_{eq} = 0.59–0.60%, wherein the total content of (Ni + Cr + Cu) is reduced from 5.2 to 3.5–3.9% [14].

The authors of [24] have shown that this strength class can be achieved in a limited range of thicknesses (up to 25 mm) and in the case of using (V + Nb) microalloyed low-carbon steel with a manganese-nickel alloying composition and C_{eq} = 0.50% according to TMCP + AC technology.

However, the stable combination of strength and cold resistance for such steels with increasing sheet product thickness requires the use of two-stage hot plastic deformation with a subsequent high-intensity cooling at a rate of at least 20°C/s to a temperatures of 300°C and lower (special Q_{rh} modes). In this case, an additional introduction of 0.3% Ni, causing the critical transformation points to become lower, is worthwhile for the formation before high-temperature tempering of low-temperature transformation products such as lath bainite and martensite with high strength characteristics. In this case, vanadium should be excluded owing to its influence on the morphology of the bainitic component.

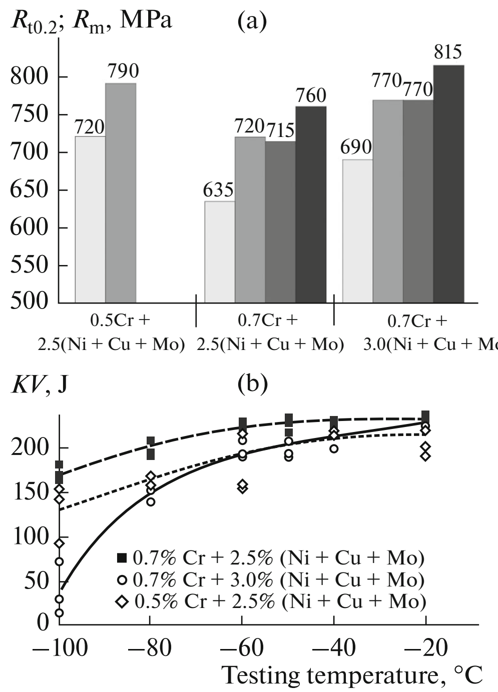

Fig. 5. Effect of Cr content and of Ni + Cu + Mo total content (a) on the average values of strength characteristics and (b) on the impact energy at a low temperature: (▢) $Rt_{0.2}$ after Q + T; (▢) Rm after Q + T; (▢) $Rt_{0.2}$ after Q_{rh} + T; (■) Rm after Q_{rh} + T.

It has been shown in [21] that the introduction of vanadium in an amount of 0.03% into low-carbon economically alloyed steel leads to an increase in the number of centers for the formation of a new phase before the ($\gamma \to \alpha$) conversion of vanadium nitrides and carbonitrides begins, intensifies the process of ferrite precipitation, and causes an increase in the critical temperature Ar_1 to provide the formation of predominantly granular structures.

In addition, the insufficient hardenability of such steels with a nickel content less than 0.7%, taking into account the limited technological capabilities to provide a preset AC rate, leads to difficulties in manufacturing sheet products of large thicknesses (over 30 mm) under industrial conditions.

The studies on phase and structural transformations occurring in high-strength economically alloyed steels with different C_{eq} values (from 0.46 to 0.61% by means of varying the content of Cr, Ni, Cu, and Mo) performed by the authors of [25] have shown that the formation of a bainite-martensitic or martensitic structure in the range of cooling rates from 5°C/s and higher, inherent in the quenching of sheets with a thickness up to 50 mm, can be achieved for steels with C_{eq} = 0.51–0.59%, ~2.5–3.0% of (Ni + Cu + Mo), and 0.5–0.7% of Cr. Increasing the chromium content over 1% at a total content of (Ni + Cu + Mo) amounting to ~2.0–2.5% promotes the occurrence of ferrite transformation at cooling rates of 5–10°C/s inherent in cooling in the middle of sheets greater than 30 mm thick.

Figure 5 presents the results of tensile and impact bending tests at a temperature ranging from –20 to –100°C for sheet products 30–35 mm thick based on economically alloyed steels having different C_{eq}: C_{eq} = 0.51% at 0.5% Cr + 2.5% (Ni + Cu + Mo); 0.54% at 0.7% Cr + 2.5% (Ni + Cu + Mo); and 0.59% at 0.7% Cr + 3.0% (Ni + Cu + Mo) after Q + T and Q_{rh} + T. All three alloying compositions provide a high stable level of impact energy up to a testing temperature of –80°C (Fig. 5b).

Sheet products with the highest C_{eq} (0.59%) under quenching both starting from a separate furnace heating and starting from a rolling heating have demonstrated strength characteristics that satisfy the requirements for steel with a strength category of 690 MPa. A 0.5% decrease in the total (Ni + Cu + Mo) content in steel sheet products with C_{eq} = 0.54% (as compared to steel with C_{eq} = 0.59%) leads to a decrease in the strength properties to a level required for steel with a guaranteed yield strength of 620 MPa. It should be noted that the use of Q_{rh} + T treatment makes it possible to provide higher values of yield strength (by 80 MPa) and tensile strength (by 40–45 MPa) in comparison with steel subjected to Q + T. Sheet products based on steel with C_{eq} = 0.51% containing 0.5% Cr and 2.5% (Ni + Cu + Mo) after Q + T treatment exhibit a combination of strength and cold resistance optimal for the strength category of 690 MPa up to –100°C (Fig. 5).

The further decrease in C_{eq} to 0.41% (~1% (Ni + Cu + Mo)) and 0.46% (0.5% Cr + 2.0% (Ni + Cu + Mo)), despite a high level of impact energy at a testing temperature of –60°C (Fig. 6b), leads to a decrease in the strength characteristics of sheet products 25–35 mm thick to a level required for steel with a strength category of 500 MPa (Fig. 6a) and significantly restricts the temperature range wherein the values required for crack resistance of sheet products remain (Fig. 6c).

As the thickness of sheet products based on economically alloyed steels with a guaranteed yield strength of 500–750 MPa increases over 50 mm, the cooling rate throughout the thickness exhibits a decrease, which in the case of an insufficient content of alloying elements leads to increasing likelihood for the formation of a predominantly bainitic structure uneven in thickness with large areas of granular and lath bainite. In this regard, to increase the hardenability of steel in the course of sheet product quenching in the thickness range of 51–100 mm, it is necessary to increase the carbon equivalent to 0.59–0.61% by means of an increase in the Cr content to 1.10–1.20% and the total content of Ni and Cu to 2.25–2.35%.

In the case of restricted content of alloying elements in high-strength cold-resistant steels for reduc-

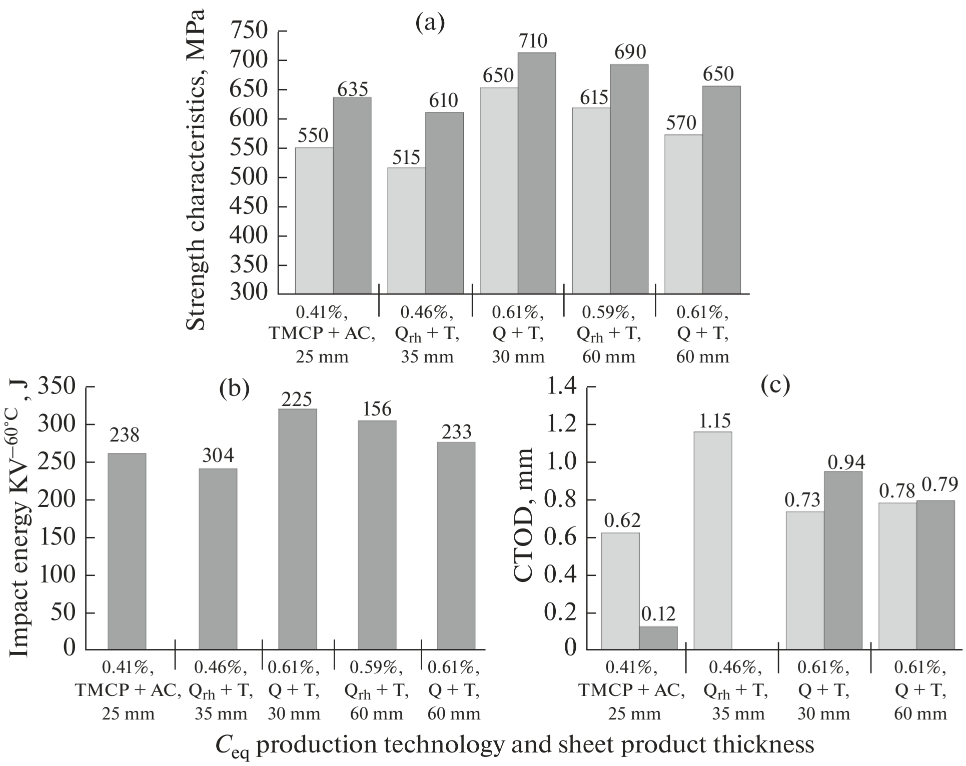

Fig. 6. Effect of C_{eq}, production technology, and sheet product thickness exerted on: (a) average strength characteristics ((▫) $Rt_{0.2}$; (▪) Rm), (b) impact energy at a testing temperature of –60°C, and (c) critical crack tip opening displacement CTOD at a low temperature ((▫) at –40°C; (▪) at –60°C).

ing the cost of their production, the microalloying can compensate the decrease in the alloying level and affect such processes as austenite grain size formation and the kinetics of their growth upon heating, the formation of carbide and carbonitride particles stable at a high temperature, the precipitation of finely dispersed carbides and carbonitrides in the course of cooling and phase transformations, the occurrence of ($\gamma \rightarrow \alpha$) transformation with the formation of a fine-grained structure, the α-phase hardening via producing solid solutions, the formation of nanosized particles in the α phase during and after cooling, and the processes of dispersion hardening of tempering [26, 27]. When using the technologies of Q_{rh} + T and Q + T, it is worthwhile to perform a separate microalloying of economically alloyed steels with niobium or vanadium.

To obtain a more uniform finely dispersed austenite structure, the high-strength, economically alloyed steels of strength categories of 500–750 MPa are predominantly microalloyed with Nb, which inhibits the growth of austenite grains under heating for rolling; promotes the inhibition of partial dynamic recrystallization; prevents the growth of new recrystallized grains after the completion of primary static recrystallization within the pauses between the passes at a rough stage and at a stage of intermediate subcooling; and extends the temperature range of austenite fragmentation, which provides the formation of a deformation substructure with small-angle boundaries in new austenitic grains [11, 28].

It has been established that to provide a stable combination of strength and impact energy throughout the thickness and the serviceability parameters at low temperatures for sheet products based on cold-resistant low-alloy (up to 100 mm thick) and economically alloyed (up to 60 mm thick) steels, including those with the Arc index, it is necessary to have narrowing of the ranges determining the carbon content and the main alloying elements specified in GOST 52927-2015 and the RMRS rules, as well as the choice of rational microalloying. This has required more detailed studies on the structure of steel, the formation of which is determined both by the level of its alloying and by the manufacturing technology, and determining the quantitative requirements for the structure parameters throughout the thickness of sheet products based on steel belonging to strength categories of 315–750 MPa, to provide specified mechanical properties and guaranteed cold resistance and crack resistance characteristics.

Development of Quantitative Requirements for Structural Parameters throughout the Thickness of Sheet Metal up to 100 mm

The studies concerning the steels of various strength categories carried out with direct participa-

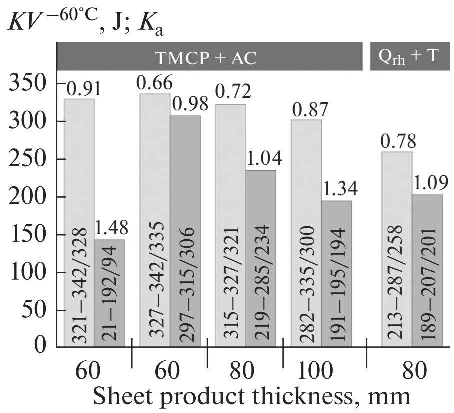

Fig. 7. Effect of anisotropy coefficient K_a on the impact energy at a test temperature of –60°C for sheet products up to 100 mm thick with strength category of 355–390 MPa after TMCP + AC and with strength category of 420–460 MPa after Q_{rh} + T. Ultimate and average yield strength values: (▫) near the surface; (▪) in the middle of the sheet thickness.

tion and under the guidance of the author have shown that, in order to guarantee the serviceability parameters of sheet products with a thickness up to 100 mm under development of a quasi-isotropic structure, in addition to the aforementioned requirements, one should fulfill other requirements that are much more stringent than those fulfilled earlier with respect to shipbuilding steels of categories D, E, and F, whose the cold-resistance properties can be monitored only through impact energy value KV at testing temperatures of –20, –40, and –60°C [8].

The idea consists in choosing assessment criteria and developing quantitative requirements for key structural parameters that determine the desired mechanical properties of steels having a yield strength of at least 315–750 MPa, a low ductile-to-brittle transition temperature T_{kb} and nil ductility temperature NDT, impact energy in the surface layers and in the middle of sheet thickness, and critical crack tip opening displacement CTOD at a test temperature of –40°C and lower, as well as a consistent assessment of a permissible heterogeneity and anisotropy level throughout the entire thickness of rolled products (i.e., maximum permissible difference in each parameter throughout the thickness).

Comprehensive requirements are proposed for the macrostructure of the initial workpiece, for the morphology, dispersion level, and the relationship between structural components, for the volume fraction and size of lath bainite areas, and for the morphological and crystallographic parameters of the structure determined with the use of TEM and EBSD analysis.

Low-Alloy Steels with Yield Strength Not Less than 315–460 MPa

Numerous studies have established [3, 29–31] that some of the key parameters of the ferrite-bainitic structure which should be strictly confined in order to obtain good viscoplastic properties and a high resistance with respect to brittle fracture are the volume fraction and extension of the areas of lath bainite that are inevitably present in the final structure of low-alloy steels.

In this regard, in order to provide guaranteed serviceability parameters of low-alloy shipbuilding steels, one should restrict the morphological anisotropy of the structure throughout the thickness of sheet products caused, firstly, by insufficient fineness of austenitic grains (owing to an incomplete recrystallization processes) and, secondly, by their strong work hardening in the course of hot deformation, as a result of which large austenite grains elongated in the direction of rolling are formed. Under a subsequent cooling, this leads to the formation of ferrite mainly along their boundaries, to an increase in the concentration of carbon and alloying elements in the remaining austenite, and to a decrease in the temperature of bainitic transformation, with the formation of large areas consisting of lath bainite.

One of the complex parameters for assessing the ferrite-bainitic structure of sheet products with a thickness up to 100 mm after thermomechanical treatment, which characterizes the presence and prominence of the priority orientation of structural components, is represented by anisotropy coefficient K_a [9, 10]. It has been found that, in order to provide high impact energy values at a testing temperature amounting to –60°C for the samples taken from the surface and the middle of sheet products with a thickness up to 100 mm, the values of K_a should not exceed 1.35 for the sheets after TMCP + AC and 1.15 for the sheets after Q_{rh} + T at a maximum permissible difference throughout sheet thickness not higher than 0.50 (Fig. 7).

Moreover, in order to obtain guaranteed serviceability parameters that satisfy the requirements for steels with the Arc index, it is necessary to toughen the requirements for the permissible value of K_a—not higher than 0.65 (Fig. 8).

When fulfilling the requirements for the anisotropy coefficient K_a in low-alloy steels of strength categories of 355–460 MPa, the volume fraction and extension of lath bainite areas should be restricted (with a quantitative assessment of their maximum size, as well as the areas of bainite with sizes ≥100, ≥300, and ≥500 μm), which, on one hand, promotes an increase in strength (approximately 70 MPa for each 15–20% of the increase in the fraction of lath bainite), but, on the other hand, significantly worsens the cold resistance characteristics. In addition, it has been found that the presence of extended areas of lath bainite is unaccept-

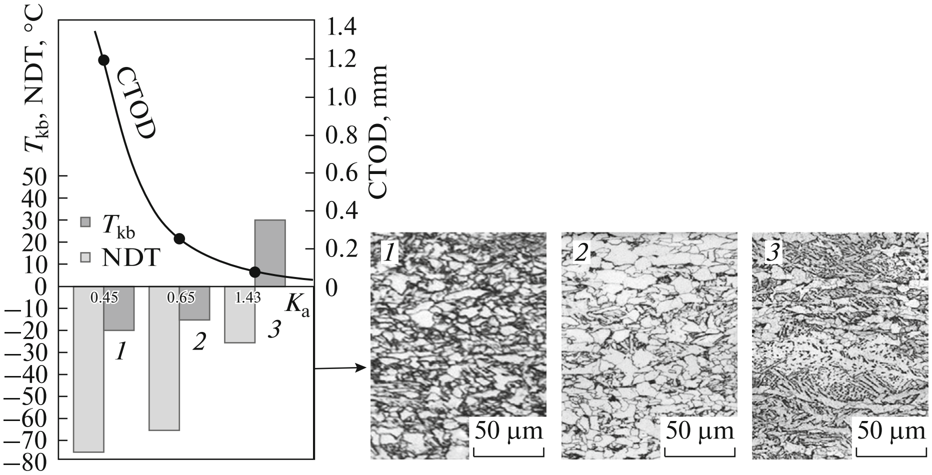

Fig. 8. Effect of anisotropy coefficient K_a of the ferrite-bainitic structure of low-alloy steel sheets 60 mm thick with strength categories of 355–390 MPa after TMCP + AC exerted on serviceability parameters.

able for providing the required critical crack tip opening displacement CTOD at low temperatures.

The required cold and crack resistance characteristics for shipbuilding steels of strength categories of 355–460 MPa can be achieved at the content of lath bainite uniformly distributed over the area of microsection, not more than 20% over the entire cross section of sheet products.

The studies carried out using the EBSD analysis showed that, along with the requirements for morphology and the relationship between structural components with the estimation of the dislocation density, the size and volume fraction of carbide precipitates on the boundaries and in the bulk of grains, and the level of anisotropy, "fine" structural parameters that characterize the internal structure of the deformed steel and describe the elements of the substructure with the boundaries of the deformation origin are significant factors determining cold resistance and crack resistance of low-alloy steels too.

Earlier, the authors of [5] studied the effect of subgrain structure parameters (the fraction of small angle boundaries, the size of structural elements at a given tolerance angle $\theta_t = 2°$) exerted on the strength and viscoplastic properties of low-alloy steel with a guaranteed yield strength of 420–460 MPa. However, previously, there were no systemic concepts concerning the effect of low angle and high angle boundary fractions (their relative extension), including with the assessment of the fraction of the boundaries corresponding to the ranges of misorientation angles of 5°–15° and 50°–62.5°, and the average D_{av} and maximum D_{max} sizes of structural elements, as well as the fraction of structural elements having size D lower than 1, 3, 5, and 10 μm for given tolerance angles $\theta_t = 5°$ and 15°, which characterizes the subgrain and grain structure of deformed steel at different points (near the surface, at 1/4 from the surface, and in the middle) throughout the thickness of rolled sheets based on the methods of complex quantitative assessment using EBSD analysis, exerted on the characteristics of strength resistance, cold resistance, and crack resistance.

Another important criterion for the formation of a ferrite-bainitic structure quasihomogeneous throughout the thickness of sheet products based on the standpoint of crystallographic and morphological similarity of structural components consists in assessing EBSD maps with overlaid images obtained for the volume fractions of α-phase structural varieties with different levels of crystal lattice distortion according to the crystal curvature scale (GAM) [17, 32, 33]. To determine of the level of structure isotropy throughout the thickness of rolled products, a quantitative assessment was performed for the identity of these mappings and the average value of parameter GAMav.

An important approach to assessing the ferrite-bainitic structure of cold-resistant low-alloy steels, not taken into account earlier, that, however, determines stably reproducible serviceability parameters, along with quantitative requirements for key structural parameters, is normalizing the range of variation of their values throughout the thickness of sheet products characterizing a permissible level of heterogeneity and anisotropy (differences between the minimum and maximum values).

Figure 9 shows the effect of the parameters of the ferrite-bainitic structure of sheet products 50–60 mm thick based on low-alloy steel determined at various points throughout the sheet thickness using EBSD analysis exerted on the values of ductile-to-brittle transition temperature T_{kb}, nil ductility temperature NDT, and critical crack tip opening displacement CTOD at testing temperature not higher than –40°C.

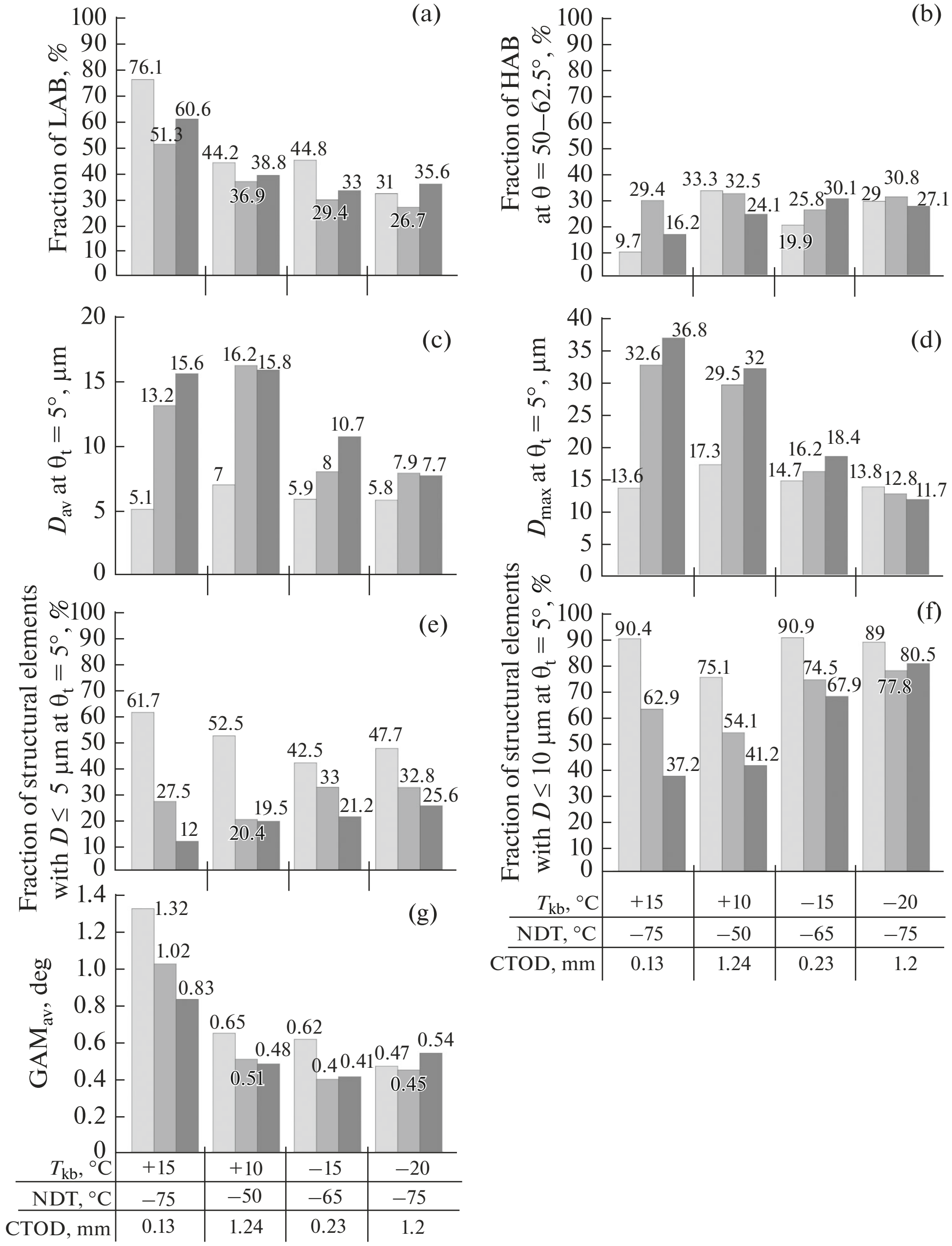

Fig. 9. Effect of the ferrite-bainitic structure parameters of low-alloy steel rolled sheets 50–60 mm thick with strength categories of 355–390 MPa after TMCP + AC determined using EBSD analysis exerted on serviceability parameters (T_{kb}, NDT, CTOD): (▫) near the surface, (▫) in a quarter of the sheet thickness, (▪) in the middle of the sheet thickness.

It has been found that the guaranteed serviceability parameters of sheet products based on low-alloy steels belonging to strength categories of 355–460 MPa with the Arc index after TMCP + AC can be achieved via restricting the values of the structure parameters and their maximum permissible difference Δ throughout sheet thickness:

–the fraction of low angle boundaries amounting to 25–40% at Δ% LAB ≤ 15% (Fig. 9a);

–the fraction of high angle boundaries corresponding to misorientation angles θ = 50°–62.5°, not less than 20% at Δ% HAB ≤ 15% (Fig. 9b);

–the average size of structural elements D_{av} for a set tolerance angle $θ_t$ = 5° not more than 11 μm for $ΔD_{av}$ ≤ 5 μm (Fig. 9c);

–the maximum size of structural elements D_{max} for a set tolerance angle $θ_t$ = 5° not more than 20 μm for $ΔD_{max}$ ≤ 5 μm (Fig. 9d);

–the fraction of structural elements with a size D not more than 5 and 10 μm for a set tolerance angle $\theta_t = 5°$ not less than 20 and 65%, respectively, at $\Delta\%D \leq 5$ μm and at $\Delta\%D \leq 10$ μm not more than 25% (Figs. 9e, 9f);

–the average value of the crystal curvature GAM_{av} not more than 0.65° at $\Delta GAM_{av} \leq 0.25°$ (Fig. 9g).

In this case, the best combination of cold and crack resistance characteristics ($T_{kb} = –20°C$, NDT = –75°C, $CTOD_{av}$ = 1.20 mm at a testing temperature of –60°C) is obtained for sheet products wherein a ferrite-bainitic structure is formed having a high level of homogeneity and isotropy throughout the thickness according to different morphological and crystallographic parameters: %LAB = 26.7–35.6% (Δ%LAB = 8.9%), %HAB = 27.1–30.8% at θ = 50–62.5°(Δ%HAB = 3.7%), D_{av} = 5.8–7.9 μm at $\theta_t = 5°$ (ΔD_{av} = 2.1 μm), D_{max} = 11.7–13.8 μm at $\theta_t = 5°$ (ΔD_{max} = 2.1 μm), $\%D_{\leq 5\ \mu m}$ = 25.6–47.7% ($\Delta\%D_{\leq 5\ \mu m}$ = 22.1%), and $D_{\leq 10\ \mu m}$ = 77. 8–89.0% ($\Delta\%D_{\leq 5\ \mu m}$ = 11.2%) at $\theta_t = 5°$, GAM_{av} = 0.47–0.54 (ΔGAM_{av} = 0.07°).

Economically Alloyed Steels with Yield Strength not Lower than 500–750 MPa

As far as high-strength steels are concerned, for a long time, the only requirement was to provide the hardenability throughout the entire thickness of the rolled sheet in order to form, after quenching, a finely dispersed bainitic or bainite-martensitic structure having a high dislocation density with a minimum content (or a complete absence) of the ferritic component. At the same time, the strength level is regulated by means of a preset relationship between martensite and bainite with different morphology, whereas viscoplastic characteristics are adjusted primarily owing to the uniformity of the structure according to size of bainitic and martensitic areas. In the course of subsequent high-temperature tempering, temperature-time conditions are provided for the formation and uniform distribution of the strengthening zones of carbide phase pre-precipitates and coherent precipitates (cementite type, alloyed with chromium and molybdenum, or special carbides such as Cr_7C_3, Mo_2C) [34].

So, for example, the structure of a 60-mm-thick sheet steel based on steel with a strength category of 500 MPa with carbon equivalent C_{eq}= 0.59–0.61%, manufactured using both Q_{rh} + T and Q + T, is formed by the areas of lath and granular bainite having different dispersion level. In this case, after Q + T, the sizes of bainitic crystallites do not exceed 30 μm, whereas after Q_{rh} + T, the size of the bainitic areas reaches 70 μm. This leads to a significant decrease in the cold-resistance characteristics of sheet products with large thickness made of high-strength steel (average values of impact energy at a testing temperature of –60°C ranging from 233 to 156 J, the values of ductile-to-brittle transition temperature T_{kb} ranging from –12 to 38°C).

It should be noted that the use of precision scientific and technological approaches to the development of hot rolling modes makes it possible to provide a high serviceability of plates made of economically alloyed high-strength steels with the use of both technologies.

The authors of [35–38] have shown that, when forming a bainitic or bainitic-martensitic structure, it is important to form "efficient grains" separated by large-angle boundaries. Just such crystalline elements that can represent not only packets, but also individual blocks, as well as structural elements with the boundaries of deformation origin and misorientation angles between them θ ≥ 5°, determine a high cold resistance and crack resistance of high-strength steels. However, this requires more detailed studies on the internal structure of bainite and martensite in chromium-nickel-molybdenum steels (laths, packets and blocks [38–41]), which has become possible with the development and application of novel certification methods for the structure of high-strength steels using EBSD analysis [17, 38, 42] in conjunction with the results of TEM.

The authors of [7] proposed the idea for assessing some structural parameters of economically alloyed steel with a yield strength of at least 750 MPa determined by means of EBSD analysis. These parameters include heterogeneity in the size of the former austenitic grains ΔD (the difference between the maximum and average size of austenitic grains) and the average size and the fraction of structural elements with a size less than 8 μm for preset tolerance angle $\theta_t = 5°$ [41–43].

These studies were performed for samples after the simulation of various rolling modes using a GLEEBLE 3800 plastometer; however, no comprehensive studies were performed up to date concerning the effect of various parameters of packet-block bainitic and bainite-martensitic structure throughout the thickness of sheet products based on economically alloyed steels with a yield strength of at least 500–750 MPa exerted on mechanical properties, as well as on cold resistance and crack resistance thereof.

To provide guaranteed serviceability parameters of sheet products with a thickness up to 60 mm made of cold-resistant economically alloyed high-strength steels with a bainitic and bainite-martensitic structure, it is necessary to develop quantitative requirements for the following key parameters and for their maximum permissible difference throughout the entire thickness of the sheets. They are: steel morphology and relationships between the structural components (with assessment of dislocation density and carbide precipitate volume fraction in the bulk and along the boundaries of grains and subgrains), as well as the fractions of low angle and high angle boundaries (including estimates of the fraction of boundaries corresponding to the ranges of misorientation angles θ = 5°–15° and θ = 50°–62.5°). In addition, these parameters include average size D_{av} and maximum size D_{max} of structural elements and the fractions of structural elements having size D not greater than 1, 3, 5, and 10 μm for given tolerance angles $\theta_t = 5°$ and $\theta_t = 15°$, as well as the average level of crystal lattice distortion GAM_{av} (with the assessment of EBSD maps of crystal lattice distortion GAM).

As far as sheet products with a thickness of 61–100 mm based on low-alloy steels and a thickness of up to 60 mm based on economically alloyed steels are concerned, these parameters require an additional refinement after further structural studies.

CONCLUSIONS

A comprehensive approach is proposed to develop requirements for choosing rational alloying and microalloying, as well as for the formation of a preset structure having an acceptable heterogeneity and anisotropy level throughout the entire thickness of sheet products. This makes it possible to assess key quantitative structure parameters and their maximum permissible difference throughout the thickness (depending on the manufacturing technology (TMCP + AC; Q_{rh} + T; Q + T) and depending on sheet thickness up to 100 mm and on strength categories from 315 to 750 MPa) for cold-resistant steels for the Arctic, including those with the "Arc" index. These assessments could provide guaranteed characteristics of strength, cold resistance (impact energy *K*V for temperatures amounting up to –60 to –80°C, ductile-to-brittle transition temperature T_{kb}, and nil ductility temperature NDT), and crack resistance according to the criterion of critical crack tip opening displacement (CTOD). The performed studies significantly extend the understanding of interrelations between the characteristics of the alloying composition and the structure and properties of low-alloy and economically alloyed steels obtained under different patterns of thermal deformation treatment.

To provide the formation of the required structural state in low-carbon low-alloy and economically alloyed steels with a yield strength of 315–750 MPa throughout the entire thickness of sheet products up to 100 mm under the industrial conditions, it is necessary to transform the thermomechanical and heat treatment processes to a considerable extent taking into account the capabilities of modern equipment with automatic control and a high level of reproducibility of precision technological techniques.

FUNDING

This work was partly supported within the scope of the project "Arctic Steel" according to state contract with the Ministry of Industry and Trade of the Russian Federation no. 16411.1810190019.09.003 of October 20, 2016.

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Translated by O. Polyakov