On the Discussion of the Classification of High-Strength Cold-Resistant Steels

M. Polyakova, O. Kupriyanova

Low-temperature technologies are increasingly used in various industries. Cold-resistant materials have gained particular popularity in the field of building machines working at low temperatures. The need for a special approach when choosing cold-resistant materials and their variety used in the production of machines, equipment, and constructions, which operate under extreme conditions (low temperatures, dynamic/static loads and (or) intense wear), created a necessity to systematize them according to a complex of mechanical properties. Despite the fact that a wide variety of products is manufactured from new cold-resistant materials, neither the scientific literature nor the regulatory documentation provide a common unified classification, which covers a wide range of categories. The article considers and summarizes various criteria used to classify cold-resistant materials, as well as preferred classification features, determines numerical ranges of constituent properties. The article points out a classification system of structural steels according to strength, cold resistance, weldability, and hardness. This article presents comprehensive systematization of scientific data of new structural cold-resistant steels for various leading industries of strength class up to 1550 MPa with corresponding characteristics of ductility and cold resistance. The use of the proposed classification of structural steels and different alloys makes it possible to select material of a certain strength class depending on operational loads of structural elements, machines, and equipment in the conditions of low temperatures, and also to predict their reliability depending on interval of low-temperature operating threshold.

KEYWORDS: IDROGENO, COMPATIBILITÀ, METALLI, NORMATIVA, PROVE MECCANICHE, ACCIAIO

INTRODUCTION

The phenomenon of cold fracture, i.e. brittle failure associated with the impact of low temperatures, was first widely discussed in connection with the rapid construction of railways at the end of the XIX century [1]. Special attention was paid to the issues of reliability, safe operation, and durability of low-temperature systems in the second half of the 1990s, because of sharply tightened the requirements for low-temperature productions, which was widely reflected in scientific research [2]. Today, this problem has become especially important due to the intensive development of the northern territories [3 - 5]. The efficiency of equipment and transport is greatly impaired in these areas in winter [6].

An analysis of the efficiency of motor-transport services in areas of harsh climate has shown that the service life of vehicles is reduced by half compared to temperate climate, and accidents and breakdowns associated with climatic conditions incapacitate up to 25% of vehicles. It was shown in scientific research [7] that the failure rate of drilling rigs in winter increases by more than 2 times compared to the summer period. The modern development of innovative

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technologies of refrigeration equipment is aimed at increasing the service life and capacity of equipment, reliability, and safety of its operation, increasing automation and robotization of production.

The urgency of low-temperature equipment is explained by the fact that low-temperature technologies are increasingly used in various industries, new processes and devices, which operate in the low-temperature range and appear annually. These are high-tech defense industries, in particular rocket and aerospace, high-energy physics, industries related to the processing, purification and liquefaction of various gases, food, medical industry, etc. [8]. The successful development of oil, gas, petrochemical, oil refining, energetic, machine-engineering, and other industries require the creation of materials that ensure high performance during the entire planned life of their operation under the influence of high pressures, corrosive environment, and temperature changes in a wide range [9]. From the standpoint of materials science, the creation of new low-temperature structural materials is an important task, ensuring high reliability and safety of structures and elements of mechanical engineering under extremely harsh operating conditions [10]. A wide range of products made of new low-temperature materials manufactured in different countries has created the need for their unified identification and classification.

Cold resistance steels are among the most advanced materials in the field of new developments, technological innovations that ensure maximum operational safety of different constructions. These steels can be used at temperatures of the climatic cold ranging from 60 to 70 below zero and at liquefaction temperatures of gases such as nitrogen, hydrogen, helium, i.e., 196-269 below zero.

However, the analysis of scientific and technical literature has shown that the issue of the classification of cold-resistant materials as well as steels of the machine-building and mining industries remains open, so far neither the scientific literature nor the regulatory documentation contains a generally accepted classification. Nowadays, there are many criteria for the classification of cold-resistant materials. Let us take a closer look at each criterion and classification features.

GENERAL CRITERIA AND CLASSIFICATION OF COLD-RESISTANT MATERIALS

According to the scientific researches it is established that cold-resistant materials can be classified according to the following criteria: chemical composition, cold resistance, weldability, strength and hardness.

Classification of materials by chemical composition

Cold-resistant materials, depending on their chemical composition, are divided into the following main groups, as it is shown in Figure 1.

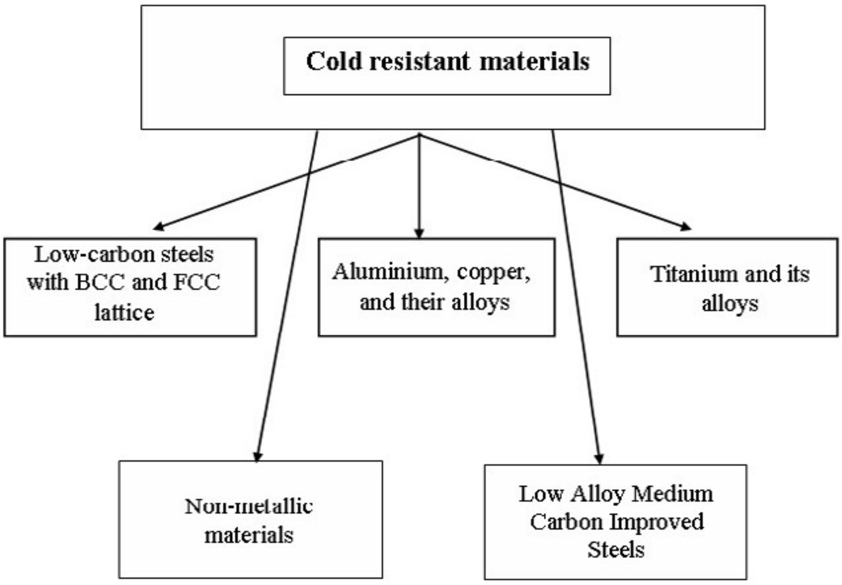

Fig.1 - Classification of cold-resistant materials by chemical composition.

Steels with BCC lattice are mainly used in the conditions of the climatic cold. The temperature limit of their application is limited by the cold breaking threshold, which varies from 0 to -60°C depending on the quality of steel and its structure. Austenitic steels with FCC lattice retain high ductility and viscosity at a temperature of -196°C [11, 12].

The transition of austenite to martensite at low temperatures is undesirable: stresses arise, there is a tendency to brittle failure. The stability of austenite is provided by an increase in the content of austenite-forming elements over 15%. The disadvantage of austenitic steels is low yield strength. Along with alloyed steel C1.2-Cr18-Ni10-Ti, stronger chrome-manganese steels (C0.3-Cr13-Al-Mn19) and special dispersion-hardening steels (C1.0-Cr11-Ni23-Ti3-Mo-B, C1.0-Cr11-Ni20-Ti3-B) are used.

Welded low-alloyed steels C0.9-Mn2-Si, C1.4-Mn2-Al-V, etc. are used for large constructions [13]. In addition to low-carbon steels, medium-carbon improved and spring steels (C0.45, C0.40-Cr, C0.65-Mn, C0.60-Si2-Al) are used. Their minimum operating temperature is -50℃. Nickel-plated steels have better cold resistance; C0.12-Cr-Ni3-Al and C0.18-Cr2-Ni4-Mo-Al steels are used at a temperature of -196°C after thermal improvement.

Martensitic-aging steels (C0.3-Cr11-Ni8-Mo2-V, C0.3-Cr9-Co14-Ni6-Mo3-Cu, C0.4-Cr14-Co13-Ni4-Mo3-Ti-W, C0.5-Cr12-Ni7-Co6-Mo4-Nb, etc.) are used for the manufacture of parts for refrigerating machines (bearings, rollers, valves, etc.) when increased strength and high hardness are necessary.

Aluminum and its alloys which have no cold-breaking threshold, remain viscous within the temperature range of -253℃ to -269℃. Fracture toughness does not practically decrease. Due to the large thermal expansion (significant thermal conductivity) of aluminum, significant thermal stresses are inevitable when structural elements are rigidly fixed in them. To reduce thermal stresses, deformation compensators are used or individual parts of the structure (for example, the necks of cryostats) are made of materials with lower thermal conductivity, for example, austenitic steels or plastics. At low temperatures (from -253℃ to -269℃), aluminum and thermally non-hardened welded alloys Al-Mn, Al-Mg2, Al-Mg5 are most commonly used. Thermally hardened alloys such as Al-Cu-Mn, Al-Cu-Mg, as well as foundry alloys are used for non-welded products operating at temperatures up to -253℃.

Copper and its alloys are ductile and do not have a cold-breaking threshold. In addition, their fracture toughness increases in the process of cooling. They are used for pipe structures, fasteners, welded housings operating at temperatures up to -269℃. Due to the higher cost compared to aluminum, copper and its alloys are increasingly being replaced by aluminum alloys.

Titanium and its alloys are not embrittled at temperatures from -196℃ to -269℃ and because of the high specific strength are used in aerospace technologies. Technically pure titanium and its single-phase alloys Ti-Al5, Ti-Al4 are widely used. They are ductile, easy to weld, and no heat treatment of the joints is required after welding. Stronger, but less ductile, Ti-Al3 and Ti-Al6 alloys with two-phase structure are used at temperatures up to -196℃. These alloys are harder to weld than single-phase ones, and annealing is required for their welded joints.

Non-metallic cold-resistant materials have lower strength and toughness compared to metals. They are used for the manufacture of thermal insulation, as well as individual parts and structural elements. Foamed polystyrene or polyurethane is used for thermal insulation. Foamed polystyrene and polyurethane are characterized by low thermal conductivity. Plastics filled with glass fiber (polyamides, polycarbonates) are used for parts and structural elements, and fluoroplast (up to -269℃) and rubber (up to -70℃) are used for movable seals.

Classification of steels and alloys by cold resistance

Normative documentation defines the recommended temperature range for each type of material used in cold-resistant structures, pressure vessels, pipelines, and other refrigeration and cryogenic equipment. The minimum operating temperature is determined by the temperature of the viscous-brittle transition, at which the viscosity drops sharply.

According to the definition, cold resistance is the ability of materials, elements, structures and their joint elements to resist brittle failure at low ambient temperatures; brittle failure is destruction (destruction of the integrity of the material) which occurs without visible plastic deformations. In scientific research on cold resistance, metal materials used at low temperatures are conventionally divided into four main groups (Figure 2):

- the first group consists of metals and alloys, which mechanical properties allow them to be used at temperatures up to -60°C, i.e. at low climatic temperatures, for the manufacture of products which can be exploited in northern regions. This group includes high-quality carbon and low-alloyed steels of ferritic and perlite classes with BCC lattice.
- the second group includes alloys that retain viscosity and ductility when cooled to -100℃. These are steels with 0.2-0.3% C, additionally alloyed with Ni, Cr, Ti, Mo. This group includes, for example, low-carbon ferritic steels with 2-5%

Ni, used at temperatures of from -60°C to -123°C.
- the third group includes alloys capable to withstand temperatures up to -196 °C (the boiling point of liquid nitrogen) without the deterioration of their properties. This includes steels of the type C1.2-Cr18-Ni10-Ti, C0.1-Ni9-Al, most alloys based on Al, Ti, Cu, which do not show tendency to brittle fracture. For unloaded structures steels of grades C1.0-Cr14-Mn14-Ni4-Ti, C0.3-Cr13-Al-Mn19, C0.7-Cr21-Mn7-Al-Ni5 are used.
- the fourth group includes alloys operating at temperatures below -196°C. Materials used in space technology, hydrogen production and consumption, and experimental physics belong to this group. Only high-alloy corrosion-resistant steels such as C0.3-Cr20-Ni16-Al-Mn6, C1.0-Cr11-Ni23-Ti3-Mo-B, some bronzes, nickel, aluminum alloys alloyed with magnesium, and titanium alloys are suitable for operation at such temperatures.

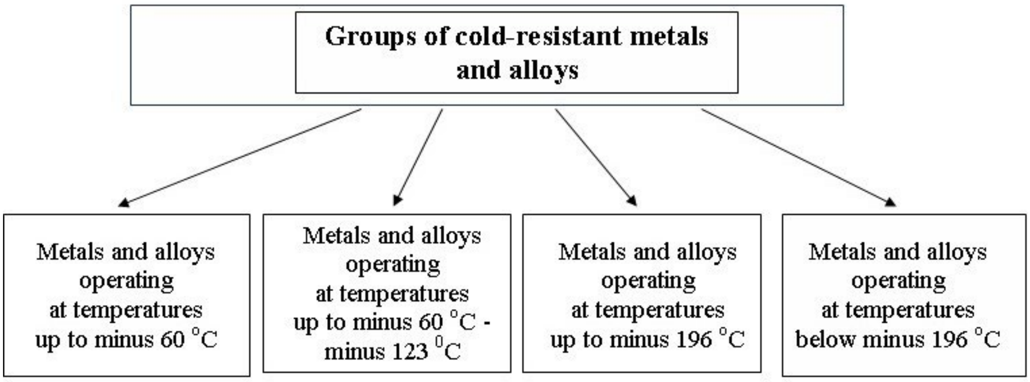

Fig.2 - Classification of metals and alloys by cold resistance.

However, the analysis showed that the intervals for the athan those in the classification given above [14]. For example, Table 1 shows examples of temperature ranges for the use of structural materials.

Tab.1 - Temperature intervals for application of structural metals and alloys.

Material	The boundary temperature of reliable operation of the material, °C	
	without additional treatment	after improving the cold resistance
Steels		
Carbon steel	-20	-50
Structural carbon steel	-30	-60
Low-alloyed steel C0.9-Mn2-Si	-40	-60
Nickel steel alloys:		
with 6 % Ni	-100	-150
with 9 % Ni	-150	-196
martensitic-aging steels C0.3-Cr9-Co14-Ni6-Mo3-Ti	-196	-253
Austenitic steels:		
chrome-manganese steel C0.3-Cr13-Al-Mn19	-130	-196
chrome-nikel steel C1.2-Cr18-Ni10-Ti	-253	-269

Invar Fe-Ni36	-269	-269
Aluminum and its alloys		
Al-Mn	-269	-269
Al-Mg	-253	-269
duraluminum Al-Cu-Mg	-196	-253
high-strength aluminum alloys	-196	-253
Titanium alloys		
Ti-Al5	-253	-269
Ti-Al3	-196	-253
Copper and its alloys		
pure Cu	-269	-269
bronze Cu-Al-Mn	-196	-253
brass Cu-Zn-Fe-Mn	-253	-269
bronze Cu-Be	-269	-269

It is shown that low-temperature materials can be used at -20℃, and at -40℃. Thus, in addition to the numerical low-temperature classification features, along with the requirement of guaranteed strength, the following groups should be added according to the requirements for guaranteed brittle fracture resistance (cold resistance):

- I group: metals and alloys without guaranteed cold resistance;
- II group: metals and alloys with guaranteed cold resistance for metal constructions operating under normal temperature conditions (specified temperature up to -20°C);
- III group: metals and alloys with guaranteed cold resistance for metal constructions operating under reduced temperature conditions (specified temperature below -20 °C, but up to -40°C);
- IV group: metals and alloys with guaranteed cold resistance, but for constructions operating at a specified temperature below -40℃, but up to -60 ℃. This indicator is regulated by the impact strength at temperatures below or at a temperature of 20℃ after mechanical aging.

Classification of cold-resistant steels and alloys by weldability

Weldability is one of the most important technological properties. Weldability is the property of a metal to form a joint in the process of welding that meets the requirements for the design and operation of the product [15 - 19]. Welding is widely used in the production of northern designs and sealed cryogenic equipment [20 - 22]. The general classification of steels by weldability is given in Table 2.

Tab.2 - General classification of cold-resistant steels and alloys according to their weldability.

Weldability	Equivalent carbon content, C_{eqv}*, %	Technological parameters			Steels and Non-ferrous metals and alloys grades	
		preheating		aeat treat-ment after welding	alloyed steels	non-ferrous metals and alloys
		prior	attendant			
good	≤0,25	-	-	-	C0.9-Mn2, C0.9-Mn2-Cu-Ti, C0.9-Mn2-Ti, C1.0-Mn2, C1.4-Mn2, C1.0-Cr-Mn-Si-Ni-Cu, C0.15-Cr-Si-Ni-Cu, C0.2-Cr-Mn-Si-Al	Al, Al-Mg1, Al-Mg2, Al-Mg3, Cu, Cu-Al9-Fe3, Cu-Be2,Cu-Cr1, Ti, Ti-Al

satisfactory	0,25-0,35	necessary	-		C0.2-Cr-Ni3-Al, C0.2-Cr-Ni, C0.2-Cr-Mn-Si-Al, C0.3-Cr, C0.3-Cr-Mo, C0.2-Cr2-Ni4-Mo-Al, C0.12-Cr-Ni2, C0.12-Cr-Ni3-Al	Cu-Sn3-Zn12-Pb5, Cu-Sn5-Zn5-Pb5, Cu-Sn8-Zn4, Cu-Sn10-Zn2, Cu58-Zn40-Mn2, Cu63-Zn34-Pb3, Cu62-Zn37-Sn1, Al-Si6, Al-Si8, Ti-Al4, Ti-Al5
limited	0,35-0,45	necessary		necessary	C0.40-Cr-Mo-V-Al, C0.40-Cr-Ni, C0.30-Cr-Mn-Si, C0.30-Cr-Mn-Si-Al, C0.35-Cr-Mo, C0.20-Cr2-Ni4-Mo-Al	Al-Cu-Mg, Ti-Al-Mo, Ti-Al-Mo-Cr-Fe-Si, Ti-Al-Mo-Zr-Si, Ti-Al-Mo-V
poor	>0,45	necessary	necessary	necessary	C0.45-Cr-Ni3-Mo-V-Al, C0.12-Cr18-Ni10-Ti, C0.50-Cr-Ni, C0.6-Cr-Si,	Cu-Al5, Cu-Al7, Cu-Sn3-Zn7-Pb5-Ni1, Cu-Sn4-Zn7-Pb5, Cu-Sn10-Pb10, Cu59-Zn-Pb1-Fe-P-Sb-Bi, Al-Cu-Mn

C_{eqv} * (equivalent carbon content) - the quantitative characteristic of weldability is determined by the formula: $C_{eqv} = C + \frac{Mn}{6} + \frac{Cr + Mo + V}{5} + \frac{Ni + Cu}{15}$, C carbon content, %; Mn, Cr, Mo, V, Ni, Cu alloying elements content, %.

According to the weldability steels are divided into four groups:
- the first group is easily weldable;
- the second group is satisfactorily weldable;
- the third group is limitedly weldable;
- the fourth group is poorly weldable.

The first group includes steels and alloys, which can be welded using conventional technology, i.e. without heating before welding and in the process of welding and without subsequent heat treatment. However, the use of heat treatment to relieve internal stresses is possible (for steels with carbon equivalent $C_{eqv} \leq 0.25\%$) [23].

The second group mainly includes steels and alloys, which do not form cracks in the process of welding under normal production conditions. The same group includes alloys that need preheating to 100-150℃, as well as preliminary and subsequent heat treatment ($0.25 < C_{eqv} < 0.35\%$) in order to prevent the formation of cracks.

The third group includes steels and alloys that are susceptible to cracking under normal welding conditions. When welding, they are subjected to preliminary heat treatment and heated to temperature of 200-250°C. In addition, most of the steels included in this group are processed after welding ($0.35 < C_{eqv} < 0.45\%$).

The fourth group includes steels and alloys that are the most difficult to weld and are susceptible to the formation of hot and cold cracks. These steels are limitedly weldable, so they are welded with mandatory preliminary heat treatment, heated to 250-300 ℃ in the process of welding and subsequent heat treatment ($C_{eqv} > 0.45\%$). But even these measures do not always prevent defects in the welds. The welding quality is low, and the strength of the welded joints is also low.

The weldability of various steels, and, in particular, the weldability of cold-resistant steels, depends on meeting the following conditions [24, 25].

1. Obtaining a welded joint, without any defects and, above all, without cold and hot cracks.
2. Obtaining a welded joint with a level of strength, ductility and viscosity that ensures proper performance under the required operating conditions.
3. The necessity to apply special technological measures in the process of welding (heating, regulation of linear energy, etc.) to meet conditions 1 and 2.
4. The necessity of heat treatment after welding of cold-resistant steels has its own characteristics related to the composition of the welded steels, their structural condition before welding.

Meeting the conditions given above will ensure a workable welding joint.

Classification of cold-resistant steels by strength and hardness

In addition to the criteria of cold resistance and weldability, the indicators of strength, hardness, and ductility also serve as the basis to choose a material. It is known that with a decrease in temperature, the strength properties of steel increase, and the viscosity and ductility decrease. Therefore, when choosing a material suitable for these conditions, the following criteria should be considered: strength at maximum operating temperature; viscosity and ductility at minimum temperature. In addition, the strength properties of each grade of steel vary greatly depending on the content of elements in the range of composition, inhomogeneity of the ingot and rolling conditions [26, 27]. The desire to make more complete use of the real strength of rolled products in structures leads to the selective separation of the entire set of metal products of this brand into separate strength groups, differing in guaranteed values of yield strength, temporary tensile strength, and guaranteed hardness at manufacturing process [28]. As practice shows, steel has been and remains the most popular material in construction, engineering, mining, and other leading industries [29-31]. This classification is necessary to systematize the entire variety of cold-resistant steels, since the classification used today is incomplete and ambiguous.

According to national standards of the Russian Federation, each grade of steel is divided into several groups due to the level of yield strength, and the guaranteed values of yield strength and tensile strength are 10-40 MPa higher for the second group than for the first group. Usually, the first strength class corresponds to rolled carbon steel of ordinary quality in a hot-rolled state, the second strength class corresponds to rolled low-alloy steel in a hot-rolled or normalized state, the third strength class corresponds to rolled low-alloy steel, in a thermally improved state. However, it is also possible to obtain rolled products of the second and third classes by thermal and thermomechanical hardening or controlled rolling [32]. It should be noted that steels with yield strength less than 265 MPa are not used as cold-resistant steels due to low strength characteristics. Today, steels with yield strength more than 800 MPa have found their wide application in various industries and are used as structural high-strength cold-resistant steels. They are often called wear-resistant steels in scientific literature, but additional requirements are imposed on these classes, along with cold resistance and strength, not in terms of wear resistance, but in terms of guaranteed hardness [33-37].

Thus, a review and analysis of the scientific and technical literature showed that cold-resistant steels are assessed and classified according to a variety of criteria. The existing classifications of steels take into account only one criterion, and the comprehensive classification of cold-resistant materials (by cold resistance and mechanical properties) is only available for shipbuilding steels, and little attention (or not at all attention) is paid to high-strength cold-resistant steels for machine-building and mining complexes, which is very important and relevant for today. In this regard, this paper proposes to classify high-strength cold-resistant steels of machine-building and mining complexes into 5 strength groups: normal, high and higher, similar to shipbuilding steels. Also it is proposed to add 2 additional groups to this classification: very high strength steel (σ_s from 800 to 1200 MPa) and ultra-high strength steel (σ_s from 1250 to 1550 MPa) with corresponding indicators of cold resistance and hardness (Table 3). The strength group number should be assigned to the steel in accordance with the values of the yield strength, for example: if σ_s is 590 MPa, steel strength class is 590 and category III should be assigned to the this steel (high strength); if σ_s is 1250 MPa, steel strength class is 1250 and category V should be assigned to this steel (ultra-high strength steel).

Tab.3 - Classification of structural steels according to strength, cold resistance, and hardness.

Conditional strength category	Strength class	Mechanical properties			Impact strength, J/sm², at least, at the test temperature, °C										Garnered hardness, HBW
		Yield strength, MPa	Ultimate tensile strength, MPa	Elongation, %	- 20	- 30	- 40	-50	-60	-70	0	- 20	- 40	-60	
		at least			KCU						KCV				
I category (normal strength)	265	265	375	25	34	34	34	34	34	29	39	39	29	+	
II category (higher strength)	295	295	430	21	39	34	34	34	34	29	39	39	29	+	+
	325	325	450	21	34	34	34	34	34	34	34	34	29	+	+
	390	390	510	19	39	34	34	34	34	29	39	39	29	+	+
III category (high strength)	440	440	590	16	39	39	39	34	34	29	39	39	+	-	-
	590	590	685	12	+	39	39	39	29	29	+	29	-	-	-
	735	735	830	10	+	39	39	39	29	29	+	29	-	-	-
IV category (high strength)	800	800	950	11	+	39	39	39	29	29	+	29	-	-	-
	850	850	980	10	+	39	39	39	29	29	+	29	30	27	27
	900	900	1000	11	+	+	+	+	+	+	+	35	30	27	27
	950	950	1000	15	+	+	+	+	+	+	+	35	30	27	27
	1000	1000	1250	10	+	+	+	+	+	+	+	35	30	27	27
	1100	1100	1400	8	+	+	+	+	+	+	+	35	30	27	27
	1200	1200	1450	8	+	+	+	+	+	+	+	35	30	27	27
V category (ultra-high strength)	1250	1250	1450-1750	8	+	+	+	+	+	+	+	35	30	27	27
	1350	1350	1750	8	+	+	+	+	+	+	+	+	20	+	+
	1450	1450	1700	7	+	+	+	+	+	+	+	+	20	+	+
	1550	1550	1850	7	+	+	+	+	+	+	+	+	16	-	-

The "+" sign means that the definition of indicators depending on the category is made before a set of statistical data.

The "-" sign means that the indicator is not regulated.

CONCLUSIONS

The paper reviewed and summarized various criteria used for the classification of cold-resistant materials, established preferred classification features, and clarified the numerical intervals of the constituent properties. The classification system of structural steels according to strength, cold resistance, and hardness was developed. The proposed criteria, unified and expanded classification of cold-resistant alloys are considered to be complex indicators of the reliability of structural elements of mining, engineering, construction, and other leading industries.

The use of the proposed classification of structural alloys makes it possible to justify the choice of design solutions and manufacturing technologies of making structures for various industries, to choose a material of a certain strength class depending on operational loads and temperatures, to predict the life of the structure depending on the interval of the low-temperature threshold of operation, and to collect the new scientific data on low-temperature structural materials.

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