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Table Of Contents

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This book systematizes reference data on the physical and chemical and technological properties of heat-resistant steels, special alloys, and cast irons.

The characteristics, properties, and production technology are given of oxidation resistant and thermostable non-metallic materials, ceramets and plastics.

The book is intended for engineering and technical personnel concerned with questions of testing and applying high-temperature materials. It may also be used by the workers of shop and plant laboratories.

INTRODUCTION

The Program of the Communist Party of the Soviet Union adopted by the Twenty-Second Congress of the Communist Party of the Soviet Union provides for intensive development of the branches of industry ensuring the greatest technical progress. In this connection there will be a particularly great increase in the significance of synthetics, metals, and alloys having special properties.

Great importance is consequently acquired by high-temperature materials, without which effective development of power machinery construction, and of the electric vacuum, radio electronic, and other branches of industry is impossible.

The thermal stability of a material is determined by the capacity of its surface to resist chemical breakdown in gaseous atmospheres at high temperatures.

We know that the metals which are the most widely used ones of all structural materials are oxidized on coming in contact with many hot gases; part of the metal becomes scale, and is irretrievably lost, the effective volume of the parts being thereby reduced.

Instances are fairly common in which the efficiency and service life of an assembly or mechanism as a whole are determined chiefly by the capacity of the surface of the parts to resist the action of high temperatures. Hence proper selection of scale-resistant materials, based on adequate knowledge of the properties of the latter, is of particular importance in creation of one structure or another.

If the material selected fails to meet the technical requirements, the service life of a part, assembly, or mechanism as a whole may be considerably curtailed. Instances of damage to machinery accompanied by grave consequences are also possible.

When high-temperature materials are properly selected, it is possible in many cases to replace valuable metals with other metals. For instance, costly metals of the platinum group are employed for the manufacture of the heating elements of large industrial high-temperature (above 1300°) furnaces. Experience has shown, however, that molybdenum, tungsten, and tantalum may be successfully used for this purpose.

The varied high-temperature materials being produced at the present time are widely employed in industry and other branches of the national economy.

What with the existing diversity of materials and the high requirements set for structures operating under the most varied conditions, the necessity arises of systematizing the available data on the properties of high-temperature metals and alloys, non-metallic materials, and coatings.

This handbook consists of three chapters.

The first chapter gives a brief description of the basic theoretical assumptions as to the oxidizability of metals and alloys. Aggressive media and methods of increasing the capacity of metals to resist oxidation are discussed in it. A description is given of the basic methods of determining thermal stability.

The second chapter contains reference tables on the chemical composition, scale resistance, and the basic physical, mechanical, and technological properties of high-temperature steels and alloys, cast irons, alloys possessing special physical properties, and non-metallic materials. An enumeration is made of the spheres of application of the materials in question in industry and other branches of the national economy.

The reference data set forth in the second chapter pertain chiefly to the thermal stability of steels, alloys, and other materials, although many of them are at the same time corrosion-resistant, heat-resistant, erosion-resistant, etc.

The third chapter is devoted to high-temperature coatings.

Voluminous material concerning high-temperature coatings has been published in recent years in domestic and foreign periodical literature.

The authors have endeavored to systematize the results of experimental work in this field. Reference data are given on the composition, properties, and technological features of production of high-temperature coatings.

Certain of the foreign data cited on high-temperature coatings are to a certain extent tentative and require verification in production from the standpoint of the possibility of applying them under the concrete conditions of operation of a given mechanism, despite the fact that, to our mind, these data may prove useful to engineering and technical personnel engaged in a search for cheaper structural materials which, in combination with protective high-temperature coatings, may be used under rigid temperature conditions.

Used as a basis for this book were works of the Soviet scientists V. I. Arkharov, G. V. Akimov, V. V. Ipat'yev, V. S. Mes'kin, A. A. Shmykov, and the foreign scientists O. Kubashevskiy and B. Hopkins, L. Colombier and I. Hochman, E. Goudremont, and others. Use was made of All-Union standards, departmental plant standards in force on 1 January 1963, various bibliographic sources containing modern achievements in the field of high-temperature materials, and certain data from the works of the present authors.

Considering the limitations imposed on size of the book, the material has been presented in condensed form, and some sections have not been included. Hence isolated omissions from the book are possible.

The authors will be grateful to readers submitting their comments on the book.

CHAPTER I

GENERAL INFORMATION ON THE PROCESSES OF OXIDATION OF METALS AND ALLOYS

1. GAS CORROSION OF METALS AND ALLOYS

Gas corrosion is the term used to designate the chemical corrosion of metals and alloys resulting from interaction of the latter with dry gases at high temperatures, and the oxidation resistance (or scale resistance) of metals and alloys is characterized by their capacity to resist gas corrosion.

The stability of operation of components at high temperatures depends on the capacity of a metal to resist gas corrosion.

The most aggressive gaseous media are oxidizing media: oxygen (O_2), water vapor (H_2O), carbon dioxide (CO_2),and sulfur dioxide (SO_2); hence the basic processes of gas corrosion which have become the most widespread in practice are associated with the oxidation of metals at high temperatures.

The oxidation of metals takes place in accordance with the reaction

$$Me + O = MeO \qquad (1)$$

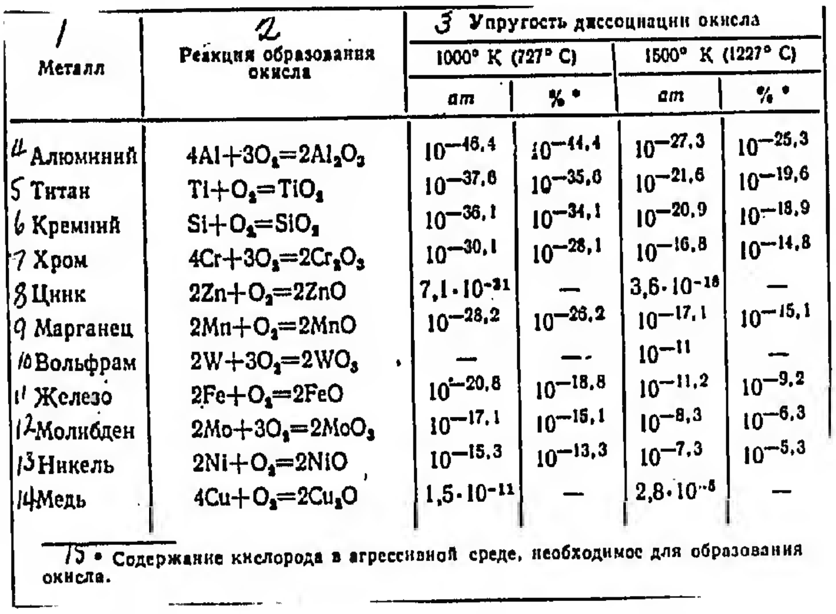
The appearance of an oxide film on metals in this case depends to a great extent on the elasticity (pressure) of dissociation of the oxides formed, which increases with elevation of the temperature. If the dissociation pressure of the oxide is less than the partial pressure of the atmospheric oxygen or other gaseous medium, the reaction in equation (1) proceeds from left to right and is accompanied by the formation of oxides; the surface of the metal will be coated with an oxide film. However, such a film will be preserved only if the oxides formed are non-volatile.

If the dissociation pressure of the oxide is greater than the partial pressure of the atmospheric oxygen, the reaction in equation (1) proceeds from right to left, that is, no conditions exist for formation of an oxide film on the surface of the metal; the oxides decompose into metal and oxygen.

The amount of the dissociation pressure of the oxides of certain metals is given in Table 1. The table shows that the least dissociation pressure is possessed by the oxides of aluminum, titanium, silicon, chromium, zinc, and manganese. The oxides of copper, nickel, molybdenum, and iron have a higher dissociation pressure.

For instance, on interaction between aluminum and oxygen in accordance with the reaction $4Al\ 3O_2 = 2Al_2O_3$, it is sufficient to have an oxygen content, at a temperature of 727°C, equalling 10^{-44} for the formation of the oxide to occur. Moreover, the lower the dissociation pressure of the oxide, the lower is the volatility of the latter. The strongest (non-volatile) oxides are formed on aluminum, titanium, chromium, manganese, and silicon.

Table 1
Dissociation Pressure of Oxides of Certain Metals



1 Металл	2 Реакция образования окисла	3 Упругость диссоциации окисла			
		1000° K (727° C)		1500° K (1227° C)	
		am	% *	*am*	% *
4 Алюминий	$4Al+3O_2=2Al_2O_3$	$10^{-46,4}$	$10^{-44,4}$	$10^{-27,3}$	$10^{-25,3}$
5 Титан	$Ti+O_2=TiO_2$	$10^{-37,6}$	$10^{-35,6}$	$10^{-21,6}$	$10^{-19,6}$
6 Кремний	$Si+O_2=SiO_2$	$10^{-36,1}$	$10^{-34,1}$	$10^{-20,9}$	$10^{-18,9}$
7 Хром	$4Cr+3O_2=2Cr_2O_3$	$10^{-30,1}$	$10^{-28,1}$	$10^{-16,8}$	$10^{-14,8}$
8 Цинк	$2Zn+O_2=2ZnO$	$7,1\cdot10^{-31}$	—	$3,6\cdot10^{-18}$	—
9 Марганец	$2Mn+O_2=2MnO$	$10^{-28,2}$	$10^{-26,2}$	$10^{-17,1}$	$10^{-15,1}$
10 Вольфрам	$2W+3O_2=2WO_3$	—	—	10^{-11}	—
11 Железо	$2Fe+O_2=2FeO$	$10^{-20,8}$	$10^{-18,8}$	$10^{-11,2}$	$10^{-9,2}$
12 Молибден	$2Mo+3O_2=2MoO_3$	$10^{-17,1}$	$10^{-15,1}$	$10^{-8,3}$	$10^{-6,3}$
13 Никель	$2Ni+O_2=2NiO$	$10^{-15,3}$	$10^{-13,3}$	$10^{-7,3}$	$10^{-5,3}$
14 Медь	$4Cu+O_2=2Cu_2O$	$1,5\cdot10^{-11}$	—	$2,8\cdot10^{-6}$	—

15 * Содержание кислорода в агрессивной среде, необходимое для образования окисла.

(1) Metal; (2) Oxide formation reaction; (3) Oxide dissociation pressure; (4) Aluminum; (5) Titanium; (6) Silicon; (7) Chromium; (8) Zinc; (9) Manganese; (10) Tungsten; (11) Iron; (12) Molybdenum; (13) Nickel; (14) Copper; (15) The oxygen content of the aggressive medium necessary for formation of the oxide.

The oxidation of metals in the initial stage represents a chemical process ending in combination of the metal with oxygen. The oxidation rate of the metal in this stage will be determined by the rate of progress of the metal-oxygen chemical reaction. Oxidation subsequently becomes a complex thermochemical process in which the chemical reaction between the metal and the gaseous medium is accompanied by diffusion of atoms (ions) of the metal into the oxide film and counter-diffusion of oxygen into the metal.

The protective properties of the oxide film formed on the metal are determined by its density, impermeability, adhesion to the metal, and strength. A porous or loose oxide film possesses no protective properties.

Three basic types of oxides are formed when metals are oxidized.

Wüstite (MeO). In accordance with this type the oxides FeO, TiO, NiO, CoO, and VO are formed. They have a cubic system crystal lattice of the rock salt type.

Magnetite (Me_3O_4). In this case the oxides $FeO\cdot Fe_2O_3$, Mn_3O_4, $MnO\cdot Fe_2O_3$, $TiO\cdot Fe_2O_3$, $NiO\cdot Fe_2O_3$, $MnO\cdot Cr_2O_3$, $NiO\cdot Cr_2O_3$, etc. are formed. These oxides have a cubic system crystal lattice of the spinel type.

Hematite (Me_2O_3). This type inclues the oxides αFe_2O_3, αCr_2O_3, Ti_2O_3, Al_2O_3, and V_2O_3. The have a crystal lattice of the rhombohedral system of the corundum type.

The type of oxide, its protective capacity, and thus also the stability of the metal toward gas corrosion, depend on a number of factors, the most important of which are the composition and temperature of the gaseous medium, the periodicity of change in the temperature, the velocity of the gas flow, the length of the time during which the metal remains in the gaseous medium, the condition of the surface of the metal, and the composition of the latter.

The relative position of the metals from the standpoint of their stability toward a gaseous medium may vary in various gaseous media at various temperatures and partial pressures.

For instance, iron heated in an atmosphere of water vapor to 700 to 1000° is oxidized more rapidly than in air. Low-alloy chromium-silicon steels behave in similar fashion (Fig. 1) [22].

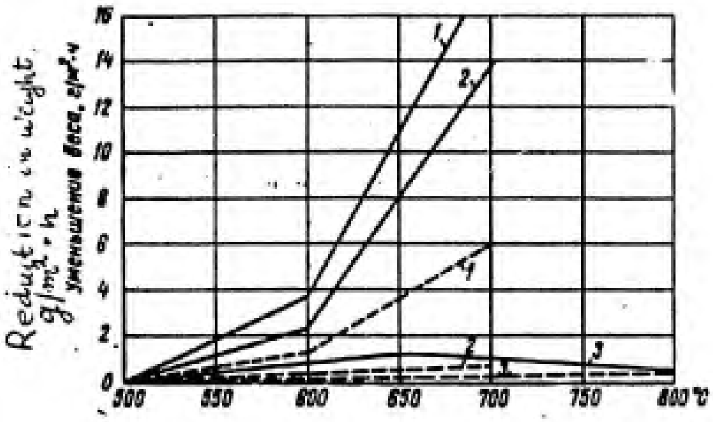


Fig. 1. Scale resistance of chromium-silicon steel in water vapor and in air. Test period 120 hours [22].
——— water vapor; air: 1 - 0.5% Mo, 1.0% Cr, 0.4% Si; 2 - 0.5% Mo, 2.5% Cr, 1.5% Si; 3- 0.5% Mo, 6.0% Cr, 2.3% Si.

Zirconium oxidizes twice as rapidly in water vapor as in air. Conversely, nickel, stellites, cast iron of the Ni-Resist brand with spherical graphite, and stainless steels Kh18N9T and Kh23H18 possess a higher corrosion resistance in water vapor than in air.

Carbon dioxide is a more aggressive medium than air, and less aggressive than water vapor. In a medium of carbon dioxide chromium-molybdenum steels undergo a certain amount of oxidation; steels alloyed with nickel and alloys based on nickel are stabler under these conditions than the chromium-molybdenum steels. In a medium of carbon dioxide, niobium suffers extensive failure even at relatively low temperatures (700°) [73].

Sulfur dioxide influences steel more actively than does air. Compounds of the FeS type are formed on heating of iron and steel in atmospheres enriched with sulfur.

Alloying with chromium and aluminum increases the stability of steel in an atmosphere of sulfur gases. At temperatures of 1000 to 1100°, chromium-nickel steels with a low nickel content are stabler toward gas corrosion in media containing sulfur than are austenitic steels. Pure nickel, relatively stable in air, in carbon dioxide, and water vapor, corrodes with extreme rapidity in a medium of sulfur dioxide even at 700°. In addition to surface corrosion, nickel and nickel steels, when heated in a gaseous atmosphere containing sulfur compounds, often undergo intercrystalline corrosion which appears in connection with the formation of the easily fusible eutectic Ni - Ni_3S_2 (melting point 650°) along the grain boundaries.

Hydrogen sulfide is also a more aggressive medium for steel than is air. In an atmosphere of hydrogen sulfide (H_2S) stainless chromium-nickel steels are stable up to temperatures of 400 to 430°; when the temperature is raised to 600 to 820°, they corrode more rapidly than do low-alloy steels. The corrosion rate in this case increases in proportion to the partial pressure of the hydrogen sulfide. The highest stability in an atmosphere of hydrogen sulfide is possessed by aluminum and its alloys with iron [73].

The influence of the partial pressure of atmospheric oxygen on the stability of a metal toward gas corrosion is graphically illustrated by the example of iron. Thus, on oxidation of iron in a gaseous medium in which the partial pressure of the oxygen is higher than the dissociation pressure of hematite (Fe_2O_3) a three-layer scale is formed which consists of three types of oxides: (1) the outer layer hematite, Fe_2O_3; the middle layer, magnetite, Fe_3O_4; (3) the lower layer, wüstite, FeO.

The last layer is in direct contact with the metal.

If the process of oxidation of iron takes place in a gaseous medium in which the partial pressure of the oxygen is lower than the dissociation pressure of hematite, a two-layer scale is formed which consists of two oxides, wüstite and magnetite.

If the oxygen concentration is lowered further, below the dissociation pressure of hematite, a single-layer scale is formed which consists of one oxide only, wüstite.

Gradual decrease in the oxygen content inward from the outer to the inner layer in contact with the metal is characteristic of each layer of the scale.

An approximate diagram of the distribution of the oxygen and iron content in scale [6] is shown in Fig. 2, from which it is to be seen that on oxidation of iron there takes place a mutual counter-diffusion of the iron into the oxide film formed and of the oxygen into the basic metal; as a result, the initial boundary of the metal is displaced inward. The solid line in the diagram shows the iron content in the various phases of the oxide film. At the same time, the maximum iron concentration corresponds to the wüstite phase (FeO) in contact with the metal, and the minimum concentration to the hematite phase (Fe_2O_3). The broken line shows the oxygen concentration in the various zones of the oxide film.

The structure of oxide films on iron is given in Fig. 3. The temperature exerts an effect not only on the general increase in the oxidation rate as a result of increase in the diffusion rate of the metal or oxygen, but also on change in the composition and structure of the scale and the interrelationships among the thicknesses of its individual layers.

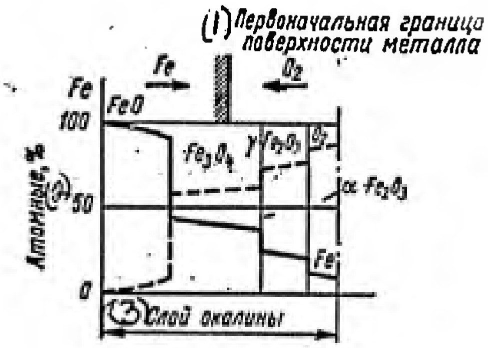


Fig. 2. Diagram of distribution of oxygen and iron concentration in scale [6]: (1) Original boundary of metal surface; (2) Atomic percent; (3) scale layer.

Figures 4 and 5 show the changes in the composition of the scale versus heating temperature in a medium of air and an iron-oxygen constitution diagram. It is to be seen from the figures that when iron is heated to a temperature below 570°, two oxides are formed on its surface, hematite (Fe_2O_3) and magnetite (Fe_3O_4). The process of oxidation of the iron under such conditions proceeds slowly due to the reduced rate of diffusion of the iron and oxygen atoms within the temperature range in question.

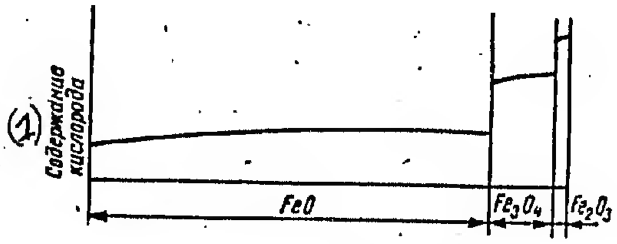


Fig. 3. Structure of scale on iron [22]: (1) oxygen content.

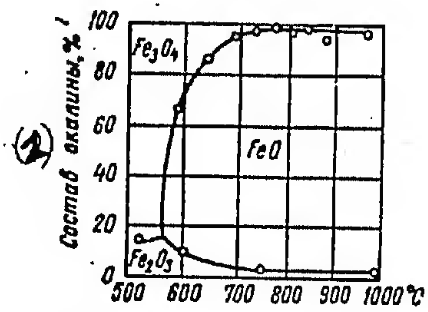


Fig. 4. Change in composition of scale on iron versus heating temperature in a medium of air [38]: (1) scale composition, %.

The wustite phase is not formed at temperatures below the eutectoid.

On heating to higher temperatures wüstite (FeO) is formed in the scale in addition to the oxides indicated. This oxide increases chiefly through diffusion of the iron ions toward the oxides of higher oxygen content (Fe_3O_4 and Fe_2O_3). As a result, the oxides of higher oxygen content become lower and less dense ones.

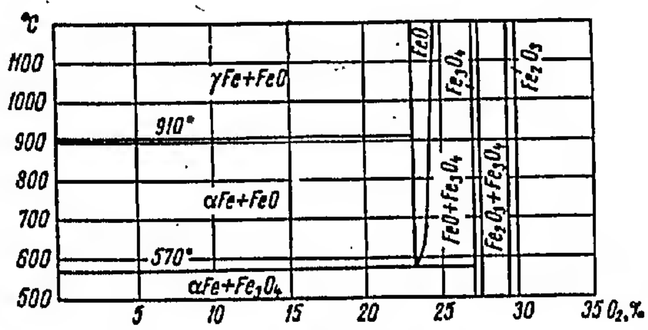


Fig. 5. Iron-oxygen constitution diagram (after Benedix and Levquist).

Oxidation of the iron increases sharply with formation of the wüstite phase. Hence in the production of high-temperature alloys based on iron, it is necessary to prevent the occurrence of the wüstite phase in the scale and to create conditions for the formation of denser oxides of the spinel type. This is achieved by the method of alloying steel and alloys with special elements a description of which is given in Chapter I, Section 3, subheading "High-temperature Alloying".

Study of the kinetics of oxidation of metals and alloys [43] shows that the rate of their oxidation in time is determined by linear, parabolic, or logarithmic functions and is expressed respectively by the following equations:

$$g = k_1\tau; \qquad (2)$$

$$g^2 = k_2\tau; \qquad (3)$$

$$g = k_3 \lg(\alpha\tau + 1), \qquad (4)$$

where

g is the quantity of oxygen entering into the reaction;
is the duration of the oxidation process;
k_1, k_2, k_3, and α are constants.

Functions (2) to (4) are represented graphically by curves 1, 2, and 3 in Fig. 6. Constant k characterizes the rate of the oxidation process and constitutes its fundamental parameter; it is determined by way of experiment. For the majority of thepprocesses of oxidation of metals and alloys constant k is subordinate to the Arrhenius equation

$$k = Ae^{-\frac{Q}{RT}}, \qquad (5)$$

where A is a constant;

Q is the energy of activation of the oxidation reaction;
R is the gas constant;
T is the absolute temperature.

The linear dependence of the oxidation rate of metals is basically determined by the rate of the metal-oxygen chemical reaction taking place on the surface. Such a dependence occurs for magnesium, calcium, and aluminum when they are oxidized in the temperature range of 400 to 500° and above; for thorium at temperatures of 350 to 500°; and for tantalum above 600°. The linear dependence of the oxidation rate is also observed on metals forming volatile oxides on heating; constant k has a negative value in this instance. One must include vanadium, tungsten, and molybdenum among the metals forming volatile oxides [65]. On metals and alloys whose oxidation process proceeds according to the linear dependence, the oxide film formed is loose; through it the oxygen has unimpeded access to the metal, and the oxidation reaction proceeds without interruption. Of course, such a film possesses no protective properties.

A film formed in accordance with the parabolic oxidation pattern is dense, but as a rule, is not a single-phase film. The composition of this film may change with time due to diffusion of the metal or oxygen atoms. Nor does an oxide film such as this ensure reliable protection against further oxidation; the oxidation process may continue in this instance. In accordance with the parabolic law, oxide films of magnesium are formed at a temperature of 400°, of molybdenum, tungsten, and aluminum at temperatures below 450°, of vanadium in the 400 to 600° temperature range, and of beryllium, chromium, iron, manganese, copper, nickel, zinc, zirconium, niobium, cadium, and other metals over a wide temperature range [65].

The best protective properties are possessed by the oxide film on metals whose oxidation process proceeds in accordance with the logarithmic dependence. In this instance, only one oxide of constant composition is formed on the surface of the metal; the oxide film is dense and impermeable; diffusion of atoms of the metal or oxygen through it is difficult. Such a film in effect protects the metal from further oxidation.

In accordance with the logarithmic law there is oxidation of copper at temperatures below 140°, iron below 200°, zinc below 225°, manganese at a temperature below 290° 65 , and of many high-temperature steels and alloys. The oxidation pattern of certain metals and alloys is shown in Table 2.

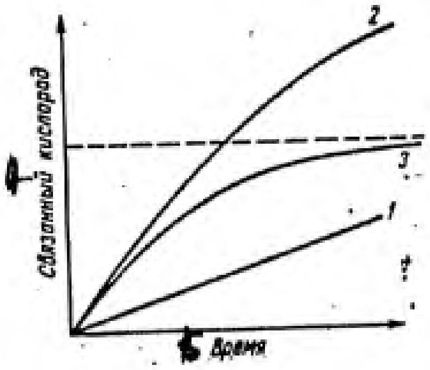


Fig. 6. Oxidation versus time curves [41]:
1 - Linear;
2 - Parabolic;
3 - Logarithmic;
4 - Bound oxygen;
5 - Time.

The protective properties of oxide films are determined largely by their continuity, that is, by their ability to coat the entire surface of the metal. The condition of continuity consists in the circumstance that the ratio of the volume of the oxide V_{ox} to the volume of the metal V_{met} expended in its formation must satisfy the following statement of inequality:

$$3 > \frac{V_{ox}}{V_{met}} > 1. \qquad (6)$$

Table 2

Oxidation Pattern of Certain Metals

And Alloys [1, 32, 39, 65]

Metal or alloy	Test conditions (gaseous medium)	Temperature °C	Oxidation pattern
Aluminum Tantalum Alloy KhN78T (E1435)	Air Air Air	Above 400 Above 600 1000	Linear $g = k_1\tau$
Kh5, 1Kh13 (EZh1) Kh25	Water vapor	500-1300	Parabolic $g^2 = k_2\tau$
Alloy KhN38VT (E1703)	Air, oxidizing and reduction atmospheres	1000-12000	Parabolic $g^n = k_2\tau$ $n = 1.84-2.43$
1Kn18N9, Kh18N9, Kh23N18 (E1417)	Oxidizing, neutral, and reduction atmospheres	1000	Logarithmic $g = k_3 lg(\alpha\tau+1)$
Kh17 (EZh17), 1Kh18N9T	Air	1100	

The properties of certain metals and their oxides are given in Table 3; the values of $\frac{V_{ox}}{V_{met}}$ characterize the continuity of the oxide film.

For such metals as magnesium, barium, and calcium, the ratio $\frac{V_{ox}}{V_{met}}$ is less than unity; the oxide film of these metals is non-continuous and possesses no protective properties. The oxides ZnO_2, V_2O_5, MoO_3, WO_3, Mn_2O_7, for which $\frac{V_{ox}}{V_{met}} > 3$, do not ensure high protective properties. Cracking of the film is possible in this case because of the occurrence of volume stresses in it.

The oxides Cr_2O_3, Al_2O_3, and SiO_2 are distinguished by high protective properties. The film of these oxides is dense and impermeable to the atoms of the metal and oxyge The ratio of the volume of these oxides to the volume of ie metal expended in their formation satisfies statement of inequality (6). However, the latter does not constitute an exhaustive condition for characterization of the protective properties of the film oxides. For instance, the iron oxides FeO, Fe_2O_3, and Fe_3O_4 satisfy statement of inequality (6), but it is known that they do not afford adequate protection of the metal from oxidation, since diffusion through them of the atoms of the metal and oxygen is possible.

Certain oxides of vanadium, tungsten, molybdenum, etc., also satisfy statement of inequality (6), but do not protect the metal from oxidation because of their volatility.

The oxides of certain noble metals (silver, platinum, palladium, etc.) do not ensure protection from oxidation at high temperatures because of the fact that their dissociation pressure is higher than the partial pressure of atmospheric oxygen.

Consequently, to determine the protective properties of an oxide it is necessary to make allowance, in addition to the volume ratios of the oxide and metal, also for the oxidation pattern of the metal, the possibility of diffusion of atoms of oxygen and the metal, and other factors affecting the stability of the oxide film.

Besides oxidizing gases, failure of a metal at high temperatures and pressures is also caused by such gaseous media as hydrogen, nitrogen, carbon monoxide, blast furnace and illuminating gases, etc. Various forms of gas corrosion may arise in a metal, depending on the nature of the aggressive medium.

Under the influence of oxidizing gases (oxygen, carbon dioxide, water vapor) the surface layer of the metal is decarbonized; the carbon burns out of the grains of cementite and a ferrite layer the thickness of which may reach 1 mm is formed between the metal and the oxide film [73]. As a result of the decarbonization, the surface hardness decreases and the fatigue strength of the metal is lowered. For carbon steels, appreciable decarbonization ensues at 550° and reaches its maximum development in the temperature range of 750 to 800°. Above 950° the rate of oxidation of the metal increases considerably more rapidly than does the decarbonization rate [22].

The corrosive effect of hydrogen on steel at high temperatures and pressures is manifested in loosening of the grain boundaries, and also in deep decarbonization due to the formation of methane (CH_4) through combination with the carbon of the steel. As a result there is a sharp drop in the mechanical strength of the steel, chiefly its impact toughness.

Chromium steels of the ferritic class, as well as high-alloy austenitic chromium-nickel and chromium-manganese steels are sufficiently stable toward the action of hydrogen at high pressures.

The action of carbon monoxide at high temperatures leads to the formation of carbonyls, such the carbonyl of iron $Fe(CO)_5$. This form of gas corrosion is accompanied by loosening of the surface of the metal which rather often reaches a considerable depth.

Among the structural materials stable toward carbonyl corrosion are austenitic chromium-nickel steels, alloys of the Ni-Cr-Mo system, brass, and copper.

Table 3

Properties Of Certain Metals And Their Oxides 2, 34

Metal, Metal oxide	Chemical symbol	Size of ionic radius, Å	$\frac{V_{ox}}{V_{met}}$	Melting point, °C
Aluminum	Al	0.57	-	660
Oxide	Al_2O_3	0.57	1.31	2050
Chromium	Cr	0.64	-	1765
Oxide	Cr_2O_3	0.64	2.02	1990
Trioxide	CrO_3	0.35	5.13	197 Decomposes
Silicon	Si	0.39	-	1420
Quartz	SiO_2	0.39	1.94	<1425
Cristobalite	SiO_2	0.39	2.21	1710
Titanium	Ti (tetragonal)	0.80	-	1725
Oxide (II)	TiO	0.80	1.22	1750
Oxide (III)	Ti_2O_3	0.69	1.47	2130
Platinum	Pt	-	-	1775
Oxide	PtO	-	1.56	550 Decomposes
Dioxide	PtO_2	-	2.45	-
Silver	Ag	1.13	-	960
Oxide	AgO	1.13	1.69	300 Decomposes
Lower oxide	Ag_2O	-	1.58	300 Decomposes
Gold	Au	1.37	-	1063
Lower oxide	Au_2O	1.37	5.58	205
Vanadium	V	0.72	-	1720
Oxide (II)	V_2O_2	0.72	1.34	2000
Oxide (III)	V_2O_3	0.65	1.77	1970
Pentoxide	V_2O_5	0.40	3.12	690
Tungsten	W	0.68	-	3400
Dioxide	WO_2	0.68	1.86	1300
Trioxide	WO_3	-	3.36	1473
Iron	Fe	0.83	-	1539
Lower oxide	FeO	0.83	1.77	1420
Mixed oxide	Fe_3O_4	-	2.09	1538 Decomposes
Oxide	Fe_2O_3	0.67	2.14	1565 Decomposes

Table 3 (Cont'd)

Metal, Metal Oxide	Chemical symbol	Size of ionic radius, Å	$\frac{V_{ox}}{V_{met}}$	Melting point, °C
Molybdenum	Mo	0.68	-	2620
Dioxide	MoO_2	0.68	2.18	-
Trioxide	MoO_3	0.62	3.45	795
Calcium	Ca	1.06	--	850
Oxide	CaO	1.06	0.63	2572
Barium	Ba	1.43	-	704
Oxide	BaO	1.43	0.73	1923
Magnesium	Mg	0.78	-	650
Oxide	MgO	0.78	0.79	2800
Nickel	Ni	0.78	-	1450
Lower oxide	NiO	0.78	1.52	2090
Palladium	Pd	-	-	1555
Oxide	PdO	-	1.66	750 Decomposes
Manganese	Mn	0.91	-	1260
Lower oxide	MnO	0.91	1.71	1650
Oxide	Mn_2O_3	0.70	2.30	1080
Heptoxide	Mn_2O_7	0.46	6.06	-
Copper	Cu	0.96	-	1083
Lower oxide	Cu_2O	0.96	1.67	1235
Oxide	CuO	0.79	1.74	1026 Decomposes
Zinc	Zn	0.83	-	420
Oxide	ZnO	0.83	1.58	1973
Peroxide	ZnO_2	-	6.77	-

A peculiar form of gas corrosion is caused by the action of mitrogen. In high-temperature steels, the diffusing nitrogen binds part of the alloying elements, chiefly aluminum, into stable nitrides; the latter in turn impede diffusion of the alloying elements into the scale, in consequence of which the oxidation resistance of the steel is lowered 22 .

2. METHODS OF DETERMINING OXIDATION RESISTANCE

The oxidation resistance of a metal is characterized by its capacity to resist oxidation at high temperatures. Quantitatively oxidation resistance is determined by the oxidation rate, i.e., the quantity of oxides forming per unit time per unit surface.

To determine the oxidation resistance use is made of various methods, of which the best known are the weight method, manometric method, centrifugal method, etc..

Weight method

The most widespread method is the weight method. By this method the oxidation resistance is determined by the weight of the scale layer, as established by the increase or loss of weight of the metal.

The oxidation resistance of steel is determined by the weight method in accordance with GOST [All-Union State Standard] 6130-52. The oxidation resistance tests must be conducted in the gaseous medium (or one approximating it in chemical composition) in which the metal will function. The samples must be in the form of plates of 60 X 30 X 2.5 to 5 mm. In the testing of rod materials, use may be made of cylindrical samples of the following dimensions:

$d = 10$ mm, $h = 20$ mm;

$d = 15$ mm, $h = 30$ mm;

$d = 25$ mm, $h = 50$ mm.

The degree of surface finish of the samples must correspond to the seventh or eighth class as given by GOST 2789-59.

The test period for carbon and low-alloy brands of steel is fixed at no less than 200 hours, with periodic sampling at intervals of 50, 100, and 200 hours, and for high-alloy steels at no less than 500 hours, with periodic sampling at intervals of 100, 200, 300, 400, and 500 hours.

The temperature of the oxidation resistance tests is fixed in keeping with the class of steel and its service conditions; for carbon and low-alloy steels in the range of 300 to 600°; for medium and high-alloy steel 600 to 1200°.

The oxidation resistance of a steel is rated by the weight difference of the samples (the increase or loss of weight) between two consecutive time intervals; for carbon and low-alloy brands of steel, from 200 to 150 hours, and from 500 to 400 hours for medium and high-alloy steels.

The corrosion rate in $g/m^2 \cdot h$ is calculated from the formulas:

in determination of the oxidation resistance by the increase in weight,

$$K_W^+ = \frac{g - g_o}{S_o t};$$

in determination of the oxidation resistance by the decrease in weight,

$$K_W^- = \frac{g_o - g_1}{S_o t},$$

where K_W is the weight index of the gas corrosion;

g_o is the initial weight of the sample, g;

g is the weight of the sample with the corrosion products after the tests, g;

g_1 is the weight of the sample after removal of the layer of scale, g;

t is the duration of the tests, h.

In determination of oxidation resistance by weight increase, the weight gain is established by weighing on analytical scales accurate to within 0.1 mg, before and after the tests. To prevent possible losses due to crumbling of the scale, the samples must be placed in porcelain crucibles first brought to constant weight by several calcinations at a high temperature. After holding in a dryer and weighing, the crucibles and samples are introduced into a furnace for the oxidation resistance tests. When the test period has elapsed, the crucibles and samples are removed from the furnace, covered with previously weighed porcelain lids, cooled, and weighed.

The oxidation resistance by weight loss is also determined according to the difference in the weights of the metal before and after the tests, with sole difference that in this case the layer of scale is first carefully removed from the surface of the metal. The scale is removed from the surface of the metal (a) by chemical or electrical scouring; (b) by reduction of the scale by atomic hydrogen; (c) by mechanical means.

The weight index of the corrosion rate, K_w in $g/m^2 \cdot h$, is converted into the depth index of the corrosion rate, Π, in mm/year, by the formula

$$\Pi = \frac{8.76\,K_w}{\gamma} \text{ mm/year.}$$

where γ is the specific gravity of the metal.

In determination of oxidation resistance by weight increase, conversion of the corrosion weight index to a depth index is possible only if the chemical composition of the scale is accurately known.

Use of the weight method of determining oxidation resistance is advisable in the event of formation of uniform corrosion during oxidation.

The oxidation resistance of steel is rated according to the results of the tests with the ten-point scale of corrosion stability given in GOST 5272-50.

The permissible degree of scale resistance is established by standards or technical specifications for the pertinent articles or components.

For study of the kinetics of oxidation of metals, use is made of the method of periodic weighing of a sample without removing it from the furnace. A diagram of such a device is shown in Fig. 7. The device consists of a vertical electric muffle furnace 1, analytical scales 8, and insulating screen 7. The sample to be tested 2 is suspended toward the pan of the analytical scales on a thin Nichrome wire 6 passed through an opening in the insulating screen and in the cover 5 of the electric furnace. The sample is heated in the combustion space of the electric furnace. To prevent a thermal effect on the analytical scales, the latter are insulated by screen 7. The temperature in the furnace is determined by thermocouple 3 connected to thermoregulator 4.

Manometric Method

With this method the oxidation resistance is determined according to the volume of the oxygen absorbed in the oxidation process. The volume of the oxygen expended in formation of the oxide film is determined by a special device (Fig. 8).

A cylindrical sample 1 secured on a platinum wire is inserted into a quartz tube 3 placed in a furnace 2 of the "Mars" type. After removal of the air, the quartz tube is filled with oxygen through a special valve 4. The volume of the oxygen expended in formation of the oxide film is determined from the difference in pressure inside the tube before and after the oxidation resistance test, as read on the manometer 5.

The quantitative expression of the corrosion rate is determined by the volume of oxygen absorbed by the metal in the process of formation of the oxide film, referred to a unit of surface of the metal per unit time

$$K_{vol} = \frac{V_o}{S_o t} \ \text{cm}^3/\text{cm}^2 \cdot \text{h},$$

where K_{vol} is the volume index of the corrosion;

V_o is the volume of the absorbed oxygen in cm^3 referred to normal conditions, i.e., $t^o = 0\ ^oC$ and $P = 760$ mm Hg;

S_o is the surface of the specimen, cm^2.

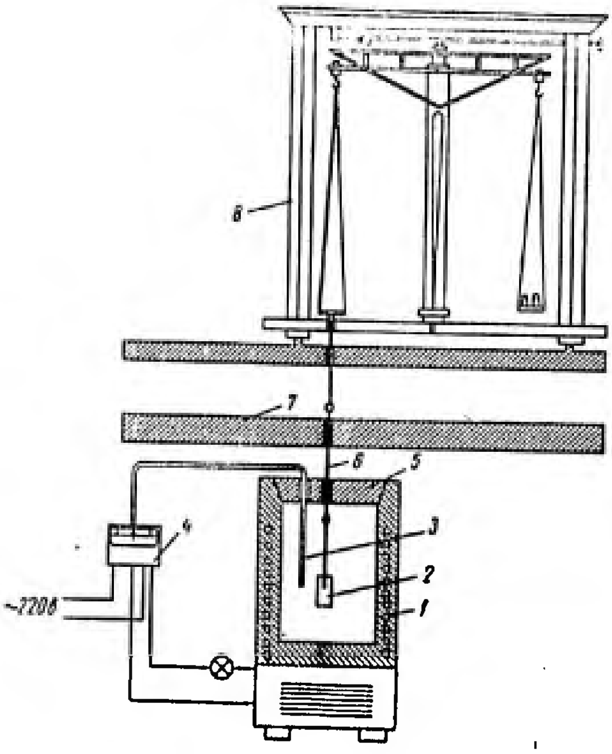


Fig. 7. Device for study of kinetics of oxidation of metals by the periodic weighing method [35].

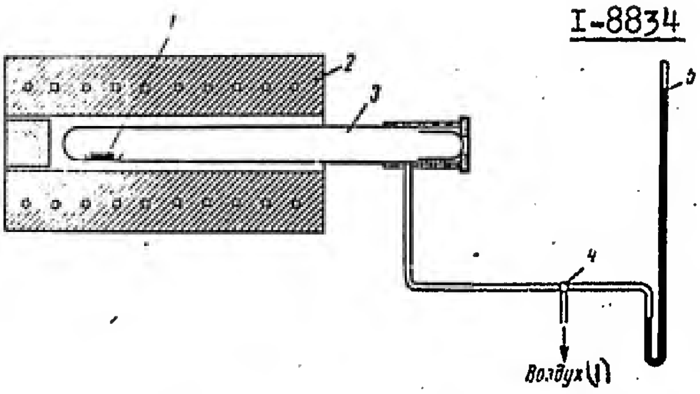


Fig. 8. Diagram of device for determination of oxygen by manometric method. [43]. (1) Air.

Determination of Oxidation Resistance by Change in the Electrical Resistance of the Metal

The change in the electrical resistance of a metal on heating may serve as an indirect method of determining its oxidation resistance. This method is frequently employed in the testing of heating elements. The wire to be tested is heated to the prescribed temperature and held for a specific period; at the same time, the amount of electric resistance is continuously recorded. With the passage of time, as the oxide film grows, the electrical resistance of the metal increases [41]. The increase in the electrical resistance is due to the decrease in the diameter of the wire or lowering of the content of alloying elements (chromium, aluminum, silicon) in the alloy as a result of expenditure of these elements in formation of the oxide film in the form of Cr_2O_3, Al_2O_3, and SiO_2.

The quantitative change in the electrical resistance in tests by the method in question may be expressed by the formula

$$K = \frac{R_1 - R_o}{R_o} \cdot 100\% \text{ during time } \underline{t},$$

where R_o is the electrical resistance of the metal before the oxidation resistance tests;
R_1 is the electrical resistance of the metal after the oxidation resistance tests during time $\underline{t}$.

Because of the reduction in the diameter of the wire in the process of its testing, the amount of change in the electrical resistance is frequently calculated per unit of cross-sectional area of the sample (mm^2 or cm^2), with a length equalling unity (cm or m), i.e., the amount of change in the resistivity is determined.

This method may be utilized in tests of sheet material or wire up to 3 mm thick, and also to reveal intercrystalline corrosion. It is not applicable to welded connections.

The oxidation resistance of heating elements is sometimes determined by durability tests by means of alternate heating and cooling. In this instance, the rapid change in temperatures impedes the formation of a firmly adhering oxide film on the surface of the metal and the oxidation process is intensified.

The durability tests consist in subjecting a wire of specific diameter to heating to a prescribed temperature, to the point of burn-through, with the current alternately switched on and off at two-minute intervals. The time to burn-through of the wire is a gauge of the oxidation resistance of the material or its durability.

Centrifugal Method

This method consists essentially in creating conditions for intensive oxidation of metals by hot gases through rapid rotation of the samples tested in the furnace space. For this purpose the samples are accommodated on the stem of the rapidly rotating shaft of a centrifugal machine. The oxidation resistance is determined by the change in the weight of the metal.

The centrifugal method ensures that more accelerated results of oxidation resistance tests will be obtained in comparison with the static methods. This method may be successfully used for determination of the oxidation resistance of the parts of rotating devices such as air heaters, etc.

3. METHODS OF INCREASING OXIDATION RESISTANCE AND PROTECTION AGAINST GAS CORROSION

The basic method of increasing the oxidation resistance of steel is alloying it with special elements fostering the formation of protective oxide films impervious to the action of an aggressive gaseous medium.

Protection against gas corrosion is accomplished by applying coatings to the surface of metals and alloys or by creating a protective atmosphere.

Oxidation resistance alloying

The basic alloying elements imparting to steel the highest capacity to resist gas corrosion are chromium, aluminum, and silicon. Increase in the oxidation resistance of steel is also achieved by alloying it with titanium, zirconium, niobium, tantalum, and other elements.

The role of the alloying elements in oxidation-resistant steels is expressed above all in the circumstance that they change the composition, structure, and properties of the oxide film formed, and hence the kinetics of theoxidation process as well.

It has already been noted that when iron or unalloyed steel is oxidized, there is formed on its surface a scale consisting of three layers of oxides: Fe_2O_3, Fe_3O_4, and FeO. The latter is directly in contact with the metal.

When a suitable quantity of chromium, aluminum, or silicon is introduced into steel, these elements, because their affinity to oxygen is greater than that of iron, begin to oxidize immediately in the wüstite layer upon heating, and the dense oxides Cr_2O_3, Al_2O_3, or SiO_2 are formed. With subsequent elevation of the temperature the diffusion of the alloying elements increases, and there is formed within the scale layer a sufficient quantity of oxidation-resistant oxides of the alloying elements which prevent further oxidation of the metal.

The oxides of the alloying elements of the spinel type, such as FeO • Cr_2O_3, which are formed in high-chromium iron alloys, are characterized by particularly great protective properties.

In oxidation-resistant steels, as a result of diffusion of the alloying elements toward the surface of the metal, the concentration of these elements in the interior scale layer increases (Table 4).

Concise information is given below on the influence of various alloying elements on the oxidation resistance of steel.

Chromium when heated in air forms one type of oxide, Cr_2O_3. The capacity of pure chromium to resist oxidation at high temperatures is considerably greater than that of many other metals, and chromium steels are among the best technical alloys stable toward oxidation. The protective effect of chromium in steel is manifested from the moment of formation on its surface of a film, which consists of Cr_2O_3, $\angle(Cr \cdot Fe)_2O_3 \angle$ or FeO • Cr_2O_3.

Chromium is contained in oxidation-resistant steels and alloys in the amount of 5 to 35%. In keeping with the iron-chromium constitution diagram, oxidation-resistant steels of the martensite class have 5 to 14% chromium, and those of the ferrite class 14 to 30%. However, these limits may be shifted in the presence of other alloying components. For instance, carbon, nitrogen, manganese, and nickel expand the region of martensite steels in the direction of a higher chromium content, while silicon, tungsten, molybdenum, titanium, niobium, and aluminum contract it, lowering the upper limit of the chromium content.

The influence of chromium on the scale resistance of low and medium-carbon steel at various temperatures is illustrated in Figures 9 and 10, from which it follows that the action of the chromium becomes perceptible at a content of 3 to 5%. Steels containing 5% Cr possess satisfactory resistance to oxidation up to 600 to 700°. Increase in the chromium content to 8% raises their capacity to resist oxidation up to 800°. When the steel contains 15% Cr, the scale-resistance temperature rises to 900°, and with a content of 20 to 25% Cr, the steel becomes virtually stable at 1000 to 1100°. Further increase in the chromium content above 30% is accompanied by lowering of the technological properties of the steel in hot working by machine and in working by cutting.

The influence of chromium on the oxidation resistance of austenitic steel containing nickel and tungsten is illustrated in Fig. 11, from which it may be seen that when this steel contains chromium in the amount of 11.5 to 16%, the beginning of intensive scale formation occurs at 1000°; with increase in the chromium content to 20%, the temperature at which scale formation begins rises to 1100°; at the same time, there is an appreciable decrease in the intensity of oxidation.

Aluminum sharply increases the thermal stability of iron and steel, it forming a dense oxide film of Al_2O_3 on the surface upon heating. The protective action is achieved by virtue of the fact that diffusion through the oxide film of the aluminum or spinel, FeO • Al_2O_3 proceeds much more slowly than in iron oxides.

Table 4

Scale Composition Of Certain Oxidation-Resistant Steels And Alloys [41, 60]

Brand of steel or alloy	Content of alloying elements	
	In steel or alloy	In inner scale layer
E1437B	20% Cr 0.9% Al 77% Ni 2% Ti	46.61% Cr 2.61% Al 1.70% Ni 8.82% Ti
E1617	15% Cr 2% Al 70% Ni	25.22% Cr 9.01% Al 23.56% Ni
Kh20N80	20% Cr 80% Cr	54.6% Cr 15.7% Ni
—	23.7% Cr 7.5% Al	2.33% Cr 50.0% Al 1.4% Fe
—	30-40% Cr 70-60% Ni	61.5% Cr 7.85% Ni

Fig. 12 shows the influence of aluminum on the oxidation resistance of iron. It is to be seen from the drawing that iron alloyed with aluminum in the amount of 4% is virtually scale-resistant for 75 hours and at temperatures of 900 to 1000°. When the iron contains 6 to 10% aluminum, the oxidation resistance is preserved at a temperature of 1100 to 1150° for 5 to 2 hours.

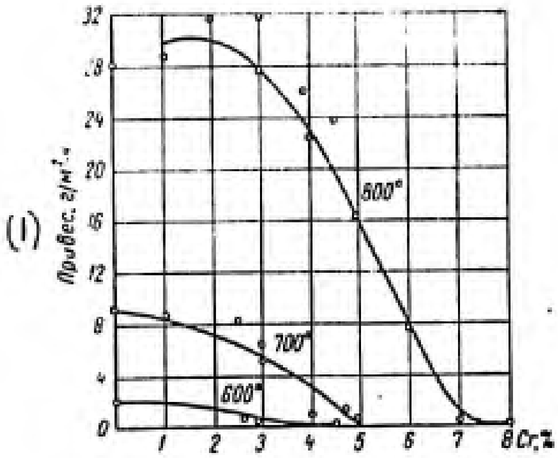


Fig. 9. Influence of chromium on scale formation on steel (0.15% C, 0.7 to 0.9% Si) in air at temperatures up to 800° [22]: (1) Weight gain, g/m² • h.

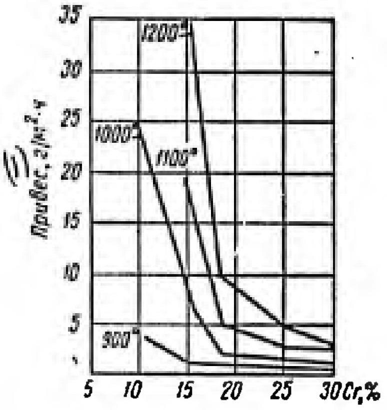


Fig. 10. Influence of chromium on scale formation on steel (0.5% C) in air at temperatures up to 1200° /22/: (1) Weight gain, g/m² . h.

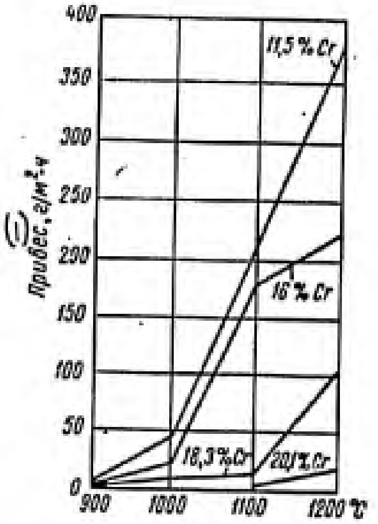


Fig. 11. Influence of chromium on the thermal stability of austenitic steel (14% Ni, 2% W) /49/: (1) Weight gain, g/m² . h.

A stronger influence on increase in oxidation resistance is exerted by additions of aluminum to chromium steels. It has been established by way of experiment that alloying of chromium steel (6% Cr) with 2% is sufficient to render it virtually oxidation-resistant at a temperature of 800° for 100 hours (Fig. 13).

The influence of aluminum on the oxidation resistance of iron-chromium alloys at a temperature of 1100° is shown in Fig. 14. It is to be seen that a high oxidation resistance for the three-component alloy Fe-Cr-Al in air at 1100° is achieved with the following proportions of alloying elements:

Al 1.5%
Cr 40%

or

Al 10%
Cr 5%

At the same time, even when the alloy contains 5% aluminum, the addition of more than 17% or 18% chromium produces no oxidation resistance effect.

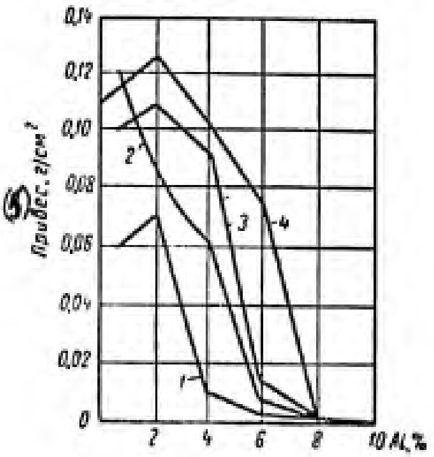


Fig. 12. Influence of aluminum on the oxidation resistance of iron alloys (I. I. Korillov):
1 -- 15 h at 900°;
2 -- 7.5 h at 1000°;
3 -- 5 h at 1100°;
4 -- 2 h at 1200°;
5 -- weight gain, g/m^2 · h.

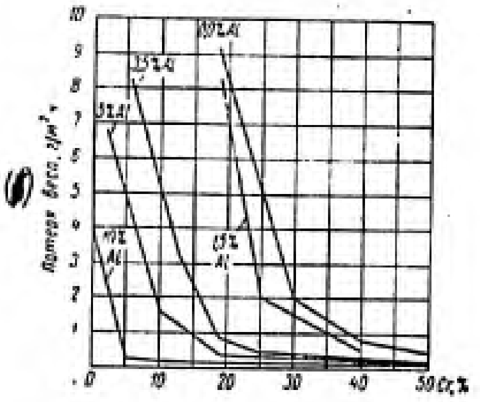


Fig. 13. Rate of oxidation of Fe-Cr-Al alloys at 1100° in air versus chromium content. Test period 240 h (Korillov and Mints): (1) Weight gain, g/m^2 · h.

The aluminum content in carbon steels as an alloying admixture virtually does not exceed 6%. With a higher aluminum content there is a sharp impairment of the technological properties of the steel due to brittleness. The outer layers of the scale of a high-alloy steel alloyed with aluminum also become brittle and flake off relatively readily under slight impacts.

Silicon has a great affinity with oxygen. The process of formation of an oxide film on the surface of a steel alloyed with silicon is accompanied predominantly by oxidation of the latter into SiO_2, a dense oxide through which diffusion of the iron is difficult.

The SiO_2 oxide film ensures a high oxidation resistance for steel when it is heated in air and in a medium containing sulfur. No protective action by silicon is manifested in an atmosphere of water vapor.

Table 5 gives data on the influence of silicon on the scale resistance of various groups of steels in air.

Chromium exerts a favorable effect on the oxidation resistance in chromium steels. The influence of silicon on the resistivity to oxidation of steel containing 5 to 6% chromium is shown in Fig. 15 and Table 6, from which it follows that alloying of the steel with 1.5 to 2.0% silicon sharply increases its oxidation resistance at a temperature of 800 to 900°. Further increase in the silicon content does not increase the oxidation resistance of chromium steel and considerably impairs its machinability.

Table 5

Influence Of Silicon On The Scale Resistance Of Various Groups of Steels (9)

Designation of Steel	Chemical composition				Weight gain, g/m^2 • h, at a temperature of °C	
	C	Si	Mn	Cr	900	1000
Carbon	0.15	0.30	0.40	-	30.0	-
Silicon	0.10	4.87	0.30	-	1.36	-
High-silicon	0.64	14.67	0.80	-	0.30	0.35
Chromium	0.30	0.26	0.37	5.49	12.55	29.10
High-chromium	0.32	1.09	0.43	17	0.40	0.89

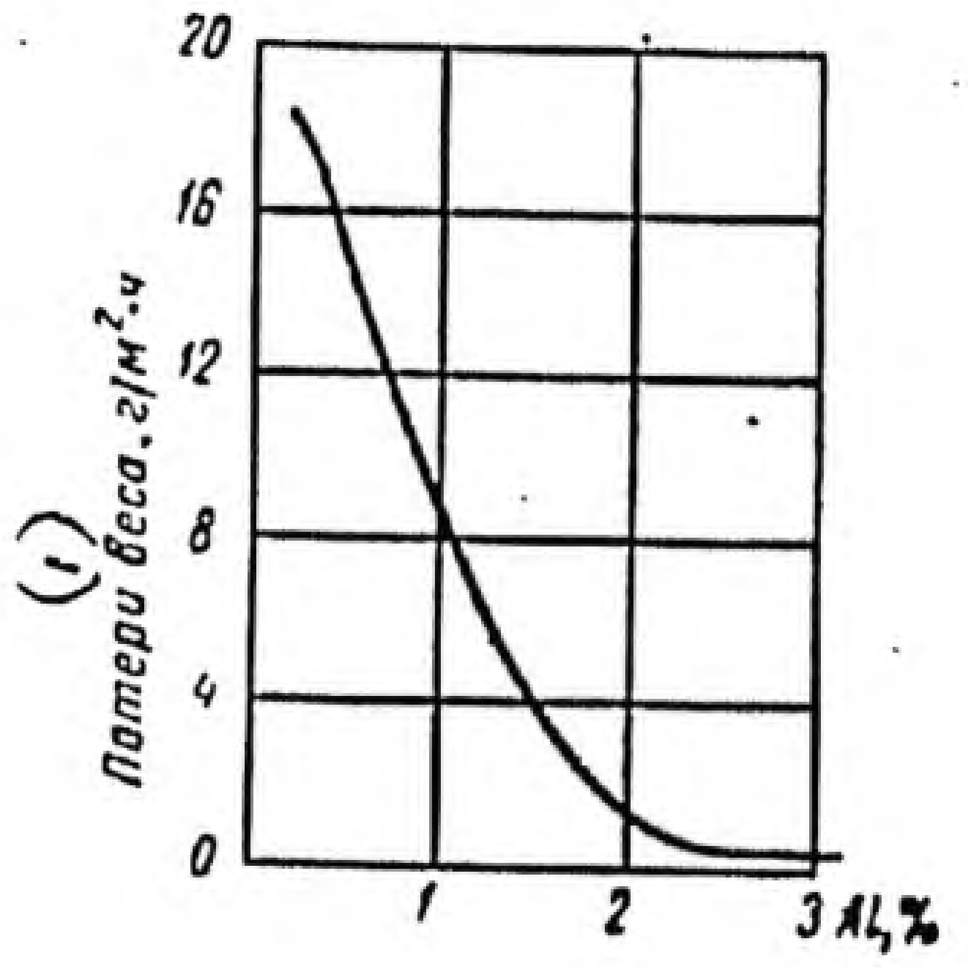


Fig. 14. Influence of aluminum on the oxidation resistance of steel (0.15% C, 6% Cr, 0.5% Mo, 100 h at 800 ° (Goudremont and Schotke): (1) Weight loss, g/m^2 • h.

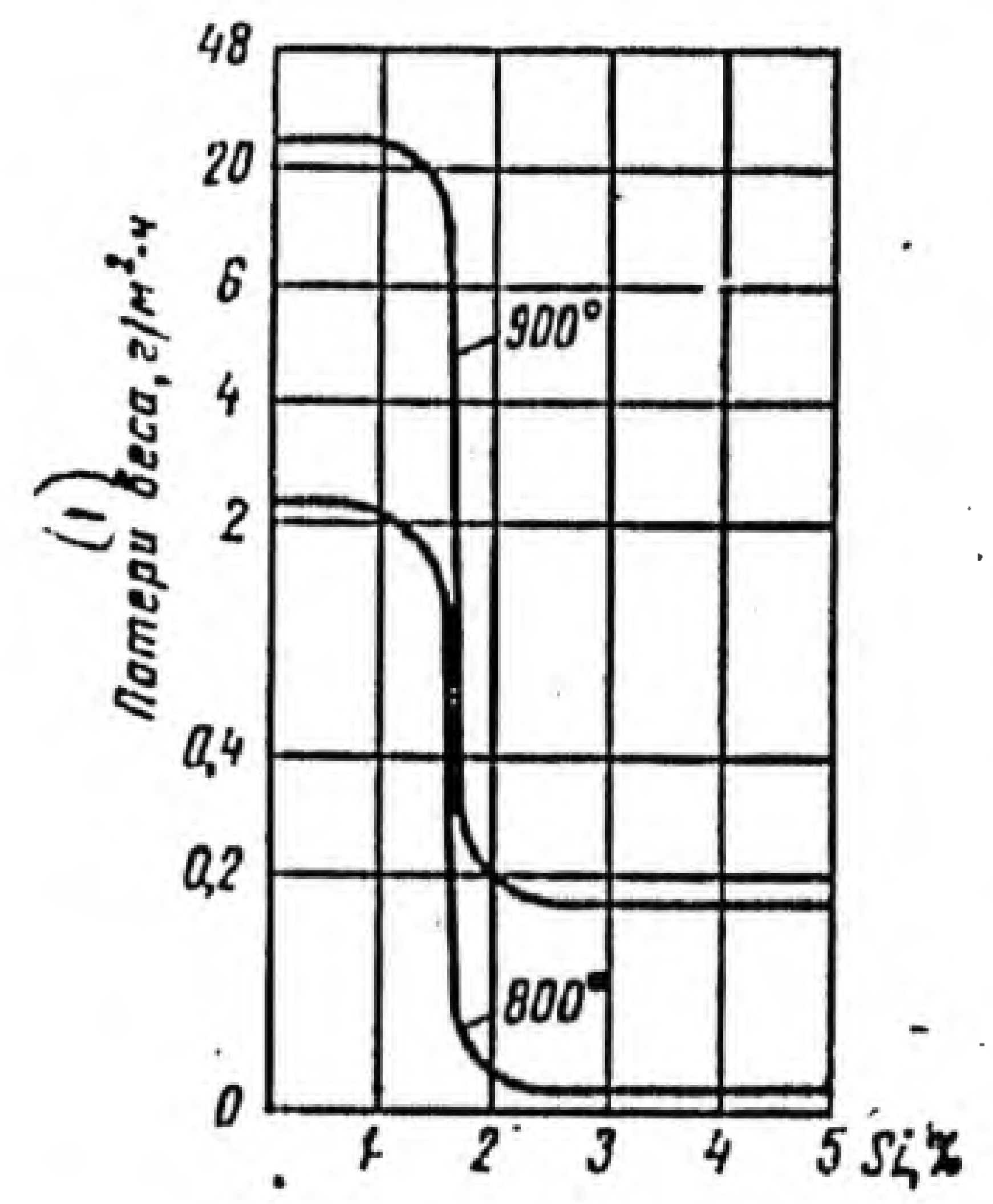


Fig. 15. Influence of silicon on the oxidation resistance of steel containing 6% Cr (Goudremont and Schotke).

Nickel has less affinity with oxygen and oxidizes less intensively than iron. On combination with oxygen, nickel forms oxides of the NiO type, which melt at a temperature of 2090°.

In alloys with iron, nickel in the amount of 2 to 6% has little effect on the stability toward oxidation in air.

Some increase in the oxidation resistance is observed in iron-nickel alloys containing up to 50% nickel/43/.

Table 6

Influence Of Silicon On The Oxidizability Of Chromium Steel/9/

(1) Содержание кремния %	(2) Увеличение веса, $г/м^2 \cdot ч$, при температуре, °C				
	700	800	900	1000	1100
0,26	1,08	3,20	12,55	29,10	46,92
1,01	—	0,03	10,40	24,48	26,48
1,87	0,08	0,03	0,06	21,93	26,42
2,25	—	—	0,03	20,06	25,43

The influence of nickel on the scale resistance of steel in air is shown in Fig. 16. As may be seen from the diagram, to obtain a satisfactory oxidation resistance, it is necessary to alloy the steel with nickel within the range of no less than 20 to 30%; hence two-component alloys of iron with nickel have not come to be widely employed in practice as scale-resistant alloys. More effective action is exerted by alloying iron-chromium alloys with nickel. The influence of nickel on the oxidation resistance of iron-chromium alloys is shown in Table 7.

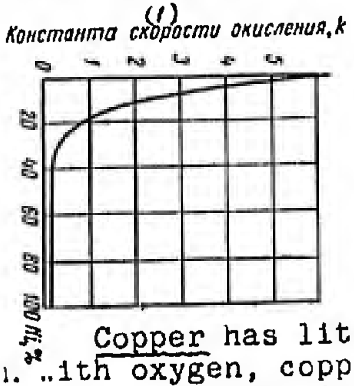


Fig. 16. The influence of nickel on the oxidation resistance of Fe-Ni alloys at a temperature of 940° in a medium of air /38/: (1) Oxidation rate constant, k.

Copper has little affinity with oxygen. On combination with oxygen, copper forms two forms of oxides, Cu_2O and CuO. The melting point of the oxides is 1235° and 1026°, respectively.

According to the data of O. Kubashevskiy and B. Hopkins /43/, small admixtures of copper in the amount of 0.8 to 2.2% improve somewhat the stability of steel toward oxidation in air at high temperatures. Works by other authors /22, 73/ point out that copper exerts no influence on the oxidation resistance of steel. In practice, copper is not introduced to increase the oxidation resistance of steel.

Beryllium oxidizes more intensively than does iron. With oxygen it forms the oxide BeO; the melting point of the oxide is 2520°. From experimental data /43/ there has been observed some increase in the oxidation resistance of steel on addition of beryllium in the amount of 2 to 4%, but beryllium is not introduced in industrial steels as an element increasing the oxidation resistance.

Boron, according to the data of certain authors /49, 73/, lowers the oxidation resistance of steel, at the same time, the low-melting oxide B_2O_3 (melting point 577°) is formed. Admixtures of boron in the amount of 0.04% to 30% chromium steel lead to complete loss of its scale resistance /73/.

Table 7

The Minimum Quantity Of Nickel Necessary For Ensuring The Oxidation Resistance* Of Iron-Chromium Alloys At Various Temperatures /49/

Chromium Content, %	Minimum amount of nickel, %, at temperatures, °C, of			
	870	980	1000	1200
11	26	30	48	56
16	0	16	30	41
21	0	0	4	9
26	0	0	3	5
31	0	0	0	8

*An amount of corrosion not exceeding 2.5% mm/yr has been adopted as the criterion of oxidation resistance.

Titanium increases the oxidation resistance of steel somewhat. It has a great affinity with oxygen. On the oxidation of steel alloyed with titanium mixed oxides are formed which have the structure of spinel, FeO • Ti_2O_3 and TiO • Fe_2O_3.

Vanadium sharply lowers the capacity of carbon steel to resist oxidation; it combines more actively with oxygen than does iron; it forms the low-melting oxide V_2O_5 (melting point 690°) /34/. The low melting vanadium pentoxide fosters the formation of loose oxides which do not protect the metal against further oxidation. Melted vanadium pentoxide dissolves protective films of other oxides, thereby activating oxidation of the steel.

The aggressive action of vanadium pentoxide is weakened by high alloying of steel and alloys with chromium, silicon, and nickel plus chromium. Thus, alloying of steel with chromium in the amount of 20 to 25% greatly reduces oxidation of the steel under high-temperature conditions under the action of V_2O_5.

Admixtures of silicon effectively weaken the harmful influence of vanadium pentoxide on the capacity of steel to resist oxidation.

Alloying of steel with nickel alone does not reduce the destructive effect of V_2O_5 on the oxide film. The destructive action of vanadium pentoxide is weakened when nickel is alloyed in combination with chromium.

Chromium-nickel alloys of the "nimonic" type are the least sensitive to the harmful influence of vanadium pentoxide.

Manganese exerts no substantial influence on the oxidation resistance of steel. Manganese combines actively with oxygen to form low-melting oxides.

Cobalt combines with oxygen to form the oxides CoO, Co_3O_4, and Co_2O_3. Alloying with cobalt contributes to some increase in the oxidation resistance of steel [43, 73].

Carbon in the carbide state lowers the oxidation resistance of steel and exerts no substantial influence on oxidation resistance if it is in a solid solution of alpha or gamma iron. In chromium and chromium-nickel steels and alloys, carbon binds the chromium into carbides, thereby retarding diffusion of the chromium toward the surface of the steel; at the same time, the protective action of the oxide film is also weakened [49].

Niobium oxidizes more intensively than does iron; with oxygen it forms the oxides NbO, NbO_2, and NbO_5. Admixtures of niobium with steel slightly increase its capacity to resist oxidation [73].

Molybdenum lowers the oxidation resistance of steel; it actively combines with oxygen and forms the volatile oxides MoO_2 and MoO_3. When heated to 200° in air, molybdenum does not oxidize and does not change its external appearance. At 300° the surface of the molybdenum is coated with an oxide film of a light blue color. In the event of heating in air to 600°, the volatility of the molybdenum oxides is relatively low (Fig. 17). With further heating the volatility of the molybdenum oxides increases, and at 871° the oxide is almost entirely volatilized.

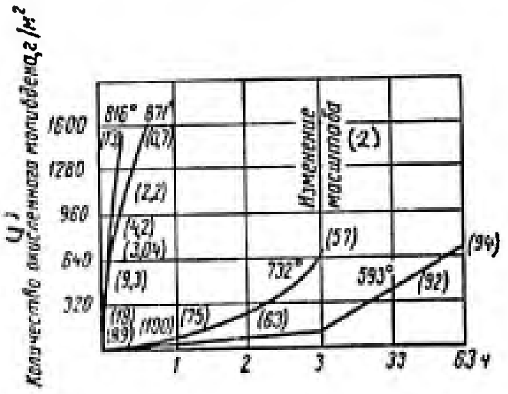


Fig. 17. Oxidation of molybdenum in air at various temperatures. The percentage of oxidized molybdenum remaining in the form of an oxide on the surface of the specimen is indicated in parentheses: (1) Amount of oxidized molybdenum, g/m²; (2) Change in scale.

In an atmosphere of oxygen in the presence of water vapor the rate of gas corrosion of steel alloyed with molybdenum increases sharply, this being due to the more intensive volatilization of the MoO_3. Volatilization of the molybdenum trioxide renders the oxide film on the steel loose and porous and creates access for the oxidizing gases directly to the metal.

Protection From Gas Corrosion With Coatings

Oxidation-resistant coatings are designed to give protection from gas corrosion of the basic metal of the parts of machines, mechanisms, instruments, and various assemblies operating at elevated and high temperatures.

The selection of oxidation-resistant coatings is determined by the conditions under which the metal operates. In keeping with these conditions, corresponding technical requirements are set for the coatings; the following are the principal such requirements:

(1) stability toward the action of an aggressive medium at high temperatures;
(2) ability not to form low-melting and volatile compounds with the elements entering into the composition of the gases;
(3) low diffusive mobility of the atoms of the elements entering into the composition of the coatings;
(4) absence of porosity;
(5) high strength of cohesion with the basic metal;
(6) high resistance to thermal and mechanical shocks;
(7) close agreement of the expansion coefficients with the basic metal at various temperatures;
(8) capacity to resist erosion wear.

The protective action of the coatings, particularly under conditions of prolonged operation, also depends on the thickness of the layer. At elevated and high temperatures, as a result of intensification of the diffusion processes, coatings of slight thickness may diffuse into the basic metal, thereby losing their protective properties.

The application of oxidation-resistant coatings is an effective method of ensuring the efficiency of articles at high temperatures, one permitting the use of cheaper construction materials for many parts and mechanisms.

In addition to protection against scale formation, a number of coatings simultaneously may serve to increase resistivity to wear in friction and erosion, and also to protect against the adhesion of scale. These properties of coatings are highly valuable ones for the parts of gas turbines, internal combustion engines, and other assemblies.

Oxidation-resistant and thermostable coatings are subdivided into metallic, non-metallic, and metal-ceramic coatings.

Metal coatings may consist of pure metals (such as chromium, nickel, etc.), and also of alloys with other elements (such as chromium-nickel, nickel-phosphorus, etc.).

Non-metallic coatings are in turn subdivided into ceramic, plastic, paint and varnish coatings, etc.

According to the method of their application oxidation-resistant coatings are divided into galvanic and thermal diffusion coatings, coatings obtained by the method of metallization, surfacing, or plating, coatings precipitated from the g gas phase, etc.

The basic data on the properties, technology of application, and use of oxidation-resistant coatings are given in Chapter III.

CHAPTER II

OXIDATION-RESISTANT AND THERMOSTABLE MATERIALS

A. STEELS, SPECIAL ALLOYS, AND CAST IRONS

1. OXIDATION-RESISTANT STEELS

The capacity of carbon steels to resist oxidation depends largely on the carbon content. With increase in the carbon content the rate of oxidation of carbon steels decreases. This pattern is especially characteristic of steels heated to temperatures above 800° [35], this being confirmed by the oxidation resistance isotherms (Fig. 18). Non-alloyed steels have not, however, found application as oxidation-resistant ones, despite the favorable influence of the carbon.

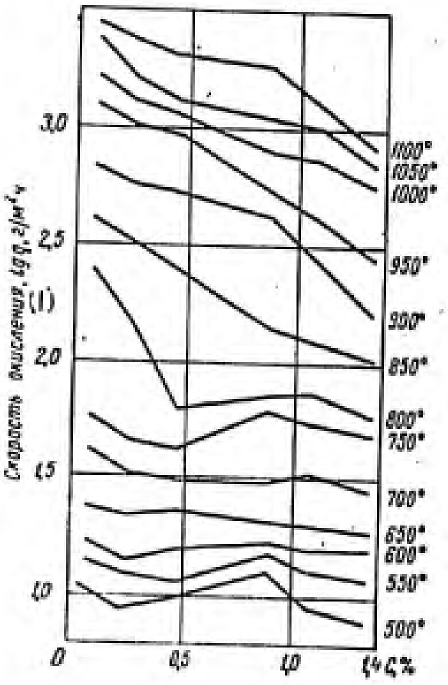


Fig. 18. Influence of carbon content on oxidation rate of carbon steels in air [35]: (1) oxidation rate, lg q, g/m² · h.

As has already been pointed out, steels alloyed with chromium, aluminum, silicon, and other elements are oxidation-resistant steels.

In conformity with GOST [All-Union State Standard] 5632-61, oxidation-resistant (scale-resistant) steels and alloys are ones which are stable toward chemical deterioration of the surface in gaseous atmospheres at temperatures above 550° and operating in an unloaded or slightly loaded state. Certain oxidation-resistant steels are simultaneously high-temperature or corrosion-resistant steels.

Chemical Composition, Physical and Mechanical Properties

The chemical composition and physical and mechanical properties of medium and high-alloy oxidation-resistant steels in accordance with GOST 5632-61 are given in Tables 8 to 10.

Table 8

Chemical Composition Of High-Temperature Steels According to GOST 5632-61

Brand of Steel Марка стали	Content of elements, % Содержание элементов, %									
	C	Si	Mn	Cr	Ni	Ti	Al	Other elements Прочие элементы	S	P
Steels of the martensite class Стали мартенситного класса										
X5** Kh5	<0,15	<0,50	<0,50	4,50—6,00	—	—	—	—	0,025	0,030
4Kh9S2 (Kh9S2, 4X9C2 (X9C2, ЭСХ8)** ESKh8)	0,35—0,45	2,00—3,00	<0,70	8,0—10,0	—	—	—	—	0,025	0,030
4Kh10S2M (Kh10S2M, 4X10C2M (X10C2M, ЭИ107)** EI107)	0,35—0,45	1,90—2,60	<0,70	9,0—10,5	—	—	—	Mo 0,70—0,90	0,025	0,030
3Kh13N7S2 (Kh13N7S2, 3X13H7C2 (X13H7C2, ЭИ72)* EI72)	0,25—0,34	2,00—3,00	<0,70	12,0—14,0	6,00—7,50	—	—	—	0,025	0,030
Steels of the martensite-ferrite class Стали мартенситно-ферритного класса										
Kh6SYu (EI428) X6CЮ (ЭИ428)*	<0,15	1,20—1,80	<0,50	5,50—7,00	—	—	0,70—1,10	—	0,025	0,030
1Kh13 (EZh1) 1X13 (ЭЖ1)***	0,09—0,15	<0,60	<0,60	12,0—14,0	—	—	—	—	0,025	0,030
Steels of the ferrite class Стали ферритного класса										
1Kh12SYu (Kh12YuS, 1X12CЮ (X12ЮС, ЭИ404)* EI404)	0,07—0,12	1,20—2,00	<0,70	12,0—14,0	—	—	1,00—1,80	—	0,025	0,030
Kh17 (EZh17) X17 (ЭЖ17)***	<0,12	<0,80	<0,70	16,0—18,0	—	—	—	—	0,025	0,035

Продолжение табл. 8

Марка стали	Содержание элементов, %									
	C	Si	Mn	Cr	Ni	Ti	Al	Прочие элементы	S	P
0Kh17T (EI645) 0X17T (ЭИ645) **	<0,08	<0,80	<0,70	16,0—18,0	—	5·C—0,80	—	—	0,025	0,035
Kh18SYu (EI484) X18CЮ (ЭИ484) *	<0,15	1,00—1,50	<0,50	17,0—20,0	—	—	0,70—1,20	—	0,025	0,035
Kh25T (EI439) X25T (ЭИ439) **	<0,15	<1,00	<0,80	24,0—27,0	—	5·C—0,80	—	—	0,025	0,035
Kh28 (EZh27, EI349) X28 (ЭЖ27, ЭИ349) **	<0,15	<1,00	<0,80	27,0—30,0	—	—	—	—	0,025	0,035
Steels of the austenite-ferrite class Стали аустенито-ферритного класса										
0Kh20N14S2 (EI732) 0X20H14C2 (ЭИ732) *	<0,08	2,00—3,00	<1,50	19,0—22,0	12,0—15,0	—	—	—	0,025	0,035
Kh20N14S2 (EI211) X20H14C2 (ЭИ211) *	<0,20	2,0—3,0	<1,50	19,0—22,0	12,0—15,0	—	—	—	0,025	0,035
Kh23N13 (EI319) X23H13 (ЭИ319) *	<0,20	<1,00	<2,00	22,0—25,0	12,0—15,0	—	—	—	0,025	0,035
Steels of the austenite class Стали аустенитного класса										
0Kh18N10 (0Kh18N9, 0X18H10 (0X18H9, ЭЯ0) *** EYa0)	<0,08	<0,80	1,00—2,00	17,0—19,0	9,0—11,0	—	—	—	0,020	0,035
Kh18N9 (1Kh18N9, X18H9 (1X18H9, ЭЯ1) *** EYa1)	<0,12	<0,80	1,00—2,00	17,0—19,0	8,0—10,0	—	—	—	0,020	0,035

Table 8 (Cont'd)

Марка стали	Содержание элементов, %									
	C	Si	Mn	Cr	Ni	Ti	Al	Прочие элементы	S	P
0Kh18Ni10T 0X18H10T (ЭИ914) *** (EI914)	≤0,08	≤0,80	1,00—2,00	17,0—19,0	9,0—11,0	5·C—0,60	—	—	0,020	0,035
Kh18Ni10T (1Kh18N9T, X18H10T (1X18H9T, ЭЯ1T) *** EYa1T)	≤0,12	≤0,80	1,00—2,00	17,0—19,0	9,0—11,0	(C—0,02) × ×5—0,70	—	—	0,020	0,035
Kh18N9T (1Kh18N9T, X18H9T (1X18H9T, ЭЯ1T) *** EYa1T)	≤0,12	≤0,80	1,00—2,00	17,0—19,0	8,0—9,50	(C—0,02) × ×5—0,70	—	—	0,020	0,035
Kh18N12T X18H12T ***	≤0,12	≤0,80	1,00—2,00	17,0—19,0	11,0—13,0	(C—0,02) × ×5—0,70	—	—	0,020	0,035
[illegible] 4X18H25C2 (X18H25C2, ЭЯ3C) *	0,32—0,40	2,00—3,00	≤1,50	17,0—19,0	23,0—26,0	—	—	—	0,020	0,035
0Kh23N18 0X23H18 **	≤0,10	≤1,00	≤2,00	22,0—25,0	17,0—20,0	—	—	—	0,020	0,035
Kh23N18 (EI417) X23H18 (ЭИ417) **	≤0,20	≤1,00	≤2,00	22,0—25,0	17,0—20,0	—	—	—	0,020	0,035
Kh25N16G7AR) X25H16Г7AP (ЭИ835) ** (EI835)	≤0,12	≤1,00	5,00—7,00	23,0—26,0	15,0—18,0	—	—	Nitrogen Азот 0,3—0,45 Бор≤0,30	0,020	0,035
Kh25N20S2 (EI283) X25H20C2 (ЭИ283) *	≤0,20	2,00—3,00	≤1,50	24,0—27,0	18,0—21,0	—	—	—	0,020	0,035
1Kh25N25TR 1X25H25TP (ЭИ813) ** (EI813)	0,07—0,12	≤0,80	1,00—2,00	23,0—26,0	24,0—27,0	1,10—1,60	—	Boron Бор <0,010	0,020	0,035

*Steels employed only as oxidation-resistant steels.

**Oxidation-resistant steels, but also used for other purposes.

***Oxidation-resistant steels, but used predominantly as high-temperature or corrosion-resistant steels.

Table 9

Physical Properties Of Oxidation-Resistant Steels [7, 23, 51]

(1) Марка стали	(2) Температура плавления, °C	(3) Удельный вес, г/см³	(4) Теплоемкость кал/г·град	(5) Коэффициент линейного расширения при 20°×10⁶	(6) Теплопроводность при 20° кал/см·сек·град	(7) Удельное электросопротивление при 20°, ом·мм²/м
(8) 4X9C2 (X9C2, ЭСX8)	—	7,62	—	11,1	0,040	—
(9) 4X10C2M (X10C2M, ЭИ107)	1480	7,60	0,11	10,7	0,060	0,75
(10) 3X13H7C2 (X13H7C2, ЭИ72)	—	8,00	—	14,5	—	—
(11) 1X13 (ЭЖ1)	1500	7,75	0,11	10,8	0,055	0,52
(12) X17 (ЭЖ17)	1500	7,68	0,11	10,5	0,063	0,56
(13) X25T (ЭИ439)	1500	7,60	0,11	10,6	—	0,67
(14) X28 (ЭЖ27, ЭИ349)	1500	7,60	0,11	10,6	—	0,70
(15) X20H14C2 (ЭИ211)	1400	7,80	0,12	14,5	0,031	0,76
(16) X23H13 (ЭИ319)	1440	7,90	0,12	16,7	0,045	0,86
(17) 0X18H10 (0X18H9, ЭЯ0)	1410	7,90	0,12	17,0	0,039	0,73
(18) X18H9 (1X18H9, ЭЯ1)	1410	7,90	0,12	16,0	0,039	0,73
(19) X18H10T (1X18H9T, ЭЯ1T)	1400	7,90	0,12	16,6	0,040	0,73
(20) X18H9T (1X18H9T, ЭЯ1T)	1425	7,90	0,12	16,7	0,035	0,75
(21) 4X18H25C2 (X18H25C2, ЭЯ3C)	1420	7,85	0,12	16,0	0,035	1,02
(22) X23H18 (ЭИ417)	1410	7,90	0,12	14,7	0,033	0,90
(23) X25H20C2 (ЭИ283)	1400	7,80	0,14	13,3	—	0,77

Explanation of Table 9:

1 - Brand of steel;
2 - Melting point, °C;
3 - Specific gravity, g/cm^3;
4 - Heat capacity, cal/g • degree;
5 --Coefficient of linear expansion at 20° X 10^6;
6 - Thermal conductivity at 20°, cal/cm • sec • degree;
7 - Specific resistance at 20°, ohm • mm^2/m;
8 - 4Kh9S2 (Kh9S2, EsKh8:);
9 - 4Kh10S2M (Kh20S2M, E1107);
10- 3Kh13N7S2 (Kh13N7S2, E172);
11- 1Kh13 (EZh1);
12- Kh17 (EZh17);
13- Kh25T (E1439);
14 - Kh28 (EZh27, E1349);
15 - Kh20N14S2 (E1211);
16 --Kh23N13 (E1319);
17 - 0Kh18N10 (0Kh18N9, EYa0);
18 - Kh18N9 (1Kh18N9, EYa1);
19 - Kh18N10T (1Kh18N9T, EYa1T);
20 - Kh18N9T (1Kh18N9T, EYa1T);
21 - 4Kh18N25S2 (Kh18N25S2, EYa3S);
22 - Kh23N18 (E1417);
23 - Kh25N20S2 (E1283)

Explanation of Table 10 (Pages 34 and 35)

1 - Brand of steel;
2 - Heat treatment conditions;
3 - Yield point, 6y, kG/mm^2;
4 - Ultimate strength, 6v;kG/mm^2;
5 - Elongation per unit length, δ%;
6 - Transverse contraction, ψ, %;
7 - Impact resistance, a_n, kG • m/cm^2;
8 - Young's modulus, E, kG/mm^2;
9 --Brinell hardness, $\frac{HB}{at}$;
10 - Kh5;
11 - Annealing 850-870°;
12 - 4Kh9S2 (Kh9S2);
13 - Annealing at 850-870°, quenching from 1050° in oil, and tempering at 740°;
14 - 4Kh10S2M (Kh10S2M, E1107);
15 - Quenching from 1010-1050° in air or oil, tempering at 720-780°;
16 - 3Kh13N7S2 (Kh13N7S2, E172);
17 - Subjected to complex heat treatment;
18 - Kh6SYu (E1428);
19 - Annealing at 750-800°;
20 - 1Kh13 (EZh1)
21 - Annealing at 740-780° with furnace cooling - Quenching from 1000-1050° in air or oil, tempering at 700-790° with cooling in air or oil;
22 - 1Kh12SYu (Kh12YuS, E1404);
23 - Annealing at 800-850°;
24 - Kh17 (Ezh17);
25 - Tempering at 760-780° with air cooling;
26 - 0kh17T (E1645);
27 - Tempering at 760-780° with air cooling
28 - By agreement with customer;
29 - Kh18SYu (E1484);
30 - Annealing at 800-850°;
31 - Kh25T (E1439);
32 - Tempering at 760-780° with air or water cooling;
33 - Kh28 (EZh27, E1349);
34 - Tempering at 760-780° with air or water cooling;
35 - 0Kh20N14S2 (E1732);
36 - Quenching from 1000-1150° in water or air;
37 - Kh20N14S2 (E1211);
38 - Quenching from 1000-1150° in water or air;
39 - Kh23N13 (E1319);
40 - Quenching from 1100-1150° in water or air;
41 - 0Kh18N10 (0Kh18N9, EYa0);
42 - Quenching from 1050-1100° in water or air;
43 - Kh18N9 (1Kh18N9, EYa1);
44 - Quenching from 1050-1100° in water or air;
45 - 0Kh18N10T (E1914);
46 - Quenching from 1050-1100° in water or air;
47 - Kh18N10T (1Kh18N9T, EYa1T);
48 - Quenching from 1050-1100° in water or air;
49 - Kh18N9T (1Kh18N9T, EYa1T);
50 - Quenching from 1050-1100° in water or air;
51 - Kh18N12T
52 - Quenching from 1050-1100° in water or air;
53 - 4Kh18N25S2(Kh18N25S2, EYa3S);
54 - Quenching from 1100-1150° in water or air;
55 - 0Kh23N18;
56 - Same as 54 above;
57 - Kh23N18 (E1417);
58 - Same as 54 above; also oil.

Table 10

Explanation of Table 10 (Cont'd)

59 - Kh25N16G7AR (E1835)
60 - Quenching from 1100-1150° in air, water, or oil;
61 - Kh25N20S2 (E1283)
62 --Quenching from 1100-1150° in air, water, or oil;
63 - 1Kh25N25TR (E1813);
64 - Same as 62 above.

Mechanical Properties of Oxidation-Resistant Steels According to GOST 5949-61 /7, 23, 61, 6, 29, 72/

1 Марка стали	2 Режим термической обработки	3 Предел текучести $\sigma_т$ $кГ/мм^2$	4 Предел прочности $\sigma_в$ $кГ/мм^2$	5 Относительное удлинение δ, %	6 Поперечное сужение ψ, %	7 Ударная вязкость $a_н$ $кГ \cdot м/см^2$	8 Модуль упругости E $кГ/мм^2$	9 Твердость по Бринелю HB
10 Х5	11 Отжиг 850—870°	17	40	24	50	10	—	—
4Х9С2 (Х9С2)	13 Отжиг 850—870°, закалка с 1050° в масле и отпуск 740°	50 60	75 90	15 20	35 55	— —	— —	— —
4Х10С2М (Х10С2М, ЭИ107)	15 Закалка с 1010—1050° на воздухе или в масле, отпуск 720—780°	75	95	10	35	2,0	19 300	248—321
16 3Х13Н7С2 (Х13Н7С2, ЭИ72)	17 Подвергается сложной термической обработке	80	120	8	25	3,0	—	341—401
Х6СЮ (ЭИ428)	Отжиг 750—800°	25	45	20	40	—	—	149
1Х13 (ЭЖ1)	Отжиг 740—780° с охлаждением с печью	24	45	25	60	—	21 000	140—180
	Закалка с 1000—1050° на воздухе или в масле; отпуск 700—790° с охлаждением на воздухе или в масле	42	60	20	60	9	—	—
1Х12СЮ (Х12ЮС, ЭИ404)	Отжиг 800—850°	35	50	15	60	—	—	—
Х17 (ЭЖ17)	Отпуск 760—780° с охлаждением на воздухе	25	40	20	50	2—8	—	140—180
0Х17Т (ЭИ645)	Отпуск 760—780° с охлаждением на воздухе	28 По согласованию с заказчиком						
Х18СЮ (ЭИ484)	Отжиг 800—850°	30	50	20	50	—	—	—
Х25Т (ЭИ439)	Отпуск 760—780° с охлаждением на воздухе или в воде	30	45	20	45	—	—	170
Х28 (ЭЖ27, ЭИ349)	Отпуск 760—780° с охлаждением на воздухе или в воде	30	45	20	45	—	—	140—190
0Х20Н14С2 (ЭИ732)	36 Закалка с 1000—1150° в воде или на воздухе	25	55	40	50	10	—	—

Table 10 (Cont'd)

Марка стали	Режим термической обработки	Предел текучести $\sigma_т$ кГ/мм²	Предел прочности $\sigma_в$ кГ/мм²	Относительное удлинение δ, %	Поперечное сужение ψ, %	Ударная вязкость $a_н$ кГ·м/см²	Модуль упругости E кГ/мм²	Твердость по Бринелю НВ
37 Х20Н14С2 (ЭИ211)	38 Закалка с 1000—1150° в воде или на воздухе	30	60	35	30	—	—	—
39 Х23Н13 (ЭИ319)	40 Закалка с 1100—1150° в воде или на воздухе	30	50	35	50	—	21 000	—
41 0Х18Н10 (0Х18Н9, ЭЯ0)	42 Закалка с 1050—1100° в воде или на воздухе	20	48	40	55	25	20 300	135—170
43 Х18Н9 (1Х18Н9, ЭЯ1)	44 Закалка с 1050—1100° в воде или на воздухе	20	50	45	55	11	20 000	—
45 0Х18Н10Т (ЭИ914)	46 Закалка с 1050—1100° в воде или на воздухе	20	50	40	55	25	—	135—170
47 Х18Н10Т (1Х18Н9Т, ЭЯ1Т)	48 Закалка с 1050—1100° в воде или на воздухе	20	52	40	55	25	20 000	140—170
49 Х18Н9Т (1Х18Н9Т, ЭЯ1Т)	50 Закалка с 1050—1100° в воде или на воздухе	20	55	40	55	25	20 300	140—170

Продолжение табл. 10

Марка стали	Режим термической обработки	Предел текучести $\sigma_т$ кГ/мм²	Предел прочности $\sigma_в$ кГ/мм²	Относительное удлинение δ, %	Поперечное сужение ψ, %	Ударная вязкость $a_н$ кГ·м/см²	Модуль упругости E кГ/мм²	Твердость по Бринелю НВ
51 Х18Н12Т	52 Закалка с 1050—1100° в воде или на воздухе	20	55	40	55	—	—	—
53 4Х18Н25С2 (Х18Н25С2, ЭЯ3С)	54 Закалка с 1100—1150° в воде или на воздухе	35	65	25	40	6	20 000	163—240
55 0Х23Н18	56 Закалка с 1100—1150° в воде или на воздухе	20	50	35	50	—	—	—
57 Х23Н18 (ЭИ417)	58 Закалка с 1100—1150° в масле, воде или на воздухе	20	50	35	50	16	—	145—210
59 Х25Н16Г7АР (ЭИ835)	60 Закалка с 1100—1150° на воздухе, в воде или в масле	33	70	40	45	—	—	—
61 Х25Н20С2 (ЭИ283)	62 Закалка с 1100—1150° на воздухе, в воде или в масле	30	60	35	50	25	—	145—210
63 1Х25Н25ТР (ЭИ813)	64 Закалка с 1100—1150° на воздухе, в воде или в масле	17	50	35	40	—	20 000	—

Technological Properties [7, 23, 28, 29, 38, 51, 72]

Steel Kh5. This steel is characterized by a tendency toward self-hardening in air. Hence after hot working or after welding the steel must be subjected to annealing at 850-870°. The steel lends itself well to machining in the annealed state.

Standard heat treatment consists of quenching from 875-900° with cooling in oil or air; tempering at 750-800°, holding, for two hours, and cooling in air. The mechanical properties of this steel vary within wide limits in keeping with the tempering temperature (Table 11).

Table 11

Mechanical Properties Of Chromium Steel Containing 0.1% C and 5.2% Cr 41

Tempering temperature, °C	Yield point σ_T, kG/mm²	Ultimate strength, σ_v, kG/mm²	Elongation per unit length, ψ, for a length of 50 mm, %
No tempering	77	127.5	15.5
550	90	119	16.5
600	72	80	20.0
650	61	70.5	23.0
700	54	64.5	25.0
750	47.5	59.6	28.0

Steel 4Kh9S2 (Kh9S2, ESKh8). Standard heat treatment: annealing at 850-950°, quenching in air or oil from 950 to 1050°, tempering at 700--850°. The steel is subject to temper brittleness and hot embrittlement in the 450-600° temperature range, and tends toward decarburization and grain growth on heating.

Steel 4Kh10S2M,(Kh10S2M, E1107). Standard heat treatment: annealing at 850-880°, furnace cooling to 750°; quenching in air or oil from 1000 to 1100°, tempering at 700-800°. The steel requires slow heating and cooling. Hard faced with stellite and nichrome. Heat treatment is required after the surfacing. Nitrides and cyanides well. Low plasticity in cold deformation.

Steel 3Kh13N7S2 (Kh13N7S2, E172). The steel is characterized by a tendency toward the formation of coarse-grained structures in hot machining.

Standard heat treatment: quenching from 1050° in water; annealing at 850-880°; tempering at 660-680°; secondary quenching from 790-810° in oil. Low plasticity in cold deformation.

Steel 1Kh13 (EZh1). Standard heat treatment: annealing at 870 to 900°; high tempering (annealing) at 740-780°; quenching in oil or water from 1000 to 1050°; tempering at 700-790°; quenching in air or oil from 1030 to 1050°; tempering at 730-750°.

The steel is capable of hardening when cooled from high temperatures in air. In the annealed state or after high-temperature tempering the steel is highly ductile; it permits deep drawing and other forms of cold pressing, as well as cold rolling.

The steel is subject to temper brittleness over the 400-550° temperature range, this being accompanied by decrease in the impact toughness. When necessary the steel may be subjected to nitriding; the recommended depth of the nitrided layer is ⩽ 0.2 mm; the hardness of the nitrided layer is ⩽ 650 HV (⩾56HRC.

The steel can be welded by the gas and arc methods; the electrodes used are of brand EF13 (GOST 9467-60, GOST 9466-60). To avoid the formation of cracks in the welding process it is necessary to carry out general or local heating of the steel to 200-250°. After welding, articles of this steel are subjected to annealing at 760-780° with slow cooling. Local tempering of the welded joint with heating to the same temperature is also possible. Dressing of welded joints without the use of concentrated impacts or dynamic loads only is permitted.

Steel Kh6SYu (E1428). Standard heat treatment: annealing at 750-800°. Hardens on cooling in air from high temperatures. The procedure for welding the steel is similar to that employed for steel 1Kh13, that is, preheating to 200-250°, welding followed by annealing, slow cooling to 600°, and further cooling in air. EF13 electrodes are used in welding. Whenever high corrosion resistance is required of the weld, it is recommended that use be made for the welding of EA1, EA2, and EA3 electrodes respectively of chromium-nickel steels Kh18N9, Kh25N15, Kh25N20.

Steel Kh17 (EZh17). The temperature range for hot working is 1150-900°; air cooling follows.

Standard heat treatment: annealing at 750-800°.

On cooling from high temperatures in air, the steel partly hardens; hence in welding the articles are preheated to 130-180°. The weldability is satisfactory; TsL-11 electrodes of steel Kh18N10B with coating. Heat treatment must be carried out immediately after welding: heating to 760-780°, air cooling.

The steel is sensitive to overheating. On heating above 1000°, the structure of the steel becomes heterogeneous and coarse-grained, as a result of which brittleness appears and the stability toward corrosion decreases.

Steel 0Kh17T (E1645). The temperature range of hot working is 1000-800°.

Standard heat treatment: tempering at 750-800°; air or furnace cooling.

The weldability of the steel is satisfactory; TsL-11 electrodes of steel Kh18N10B with coating.

The addition of titanium to 17% chromium steel eliminates the phase duality at high temperatures and grain coarseness on heating and welding, and also improves the corrosion resistance of the welded joints. The impact toughness of the welded joint is lowered ($\leqslant$1 kG • m/cm^2).

Steels Kh25T (E1439) and Kh28 (EZh27, E1349). The temperature range for hot working for both brands of steel is 1000-700°.

Standard heat treatment: tempering at 750-800°; air or water cooling.

The weldability is satisfactory. KB34 and E3B electrodes of Kh25N13 steel with coatings and ENTU-3 or F-1 electrodes of steel Kh28N4A and Kh25N5B with coatings. The stability of the welded joint toward intercrystalline and general corrosion is lower for steel Kh28. Preheating to 200° to prevent the appearance of cracks is necessary in the welding of steel Kh28. Steel Kh28 tends toward grain growth when heated above 800-850°.

Steels OKh20N14S2 (E1732) and Kh29N14S2 (E1211). The temperature range of hot working is 1150-820°; air cooling.

Standard heat treatment: quenching from 1050-1100° in water.

The weldability is satisfactory; electrodes of steel Kh25N20.

Steel Kh23N13 (E1319). The temperature range of hot working is 1150-820°; air cooling.

Standard heat treatment: quenching from 1050-1100° in air, water, or oil. In the event of protracted thermal exposures it becomes brittle and forms a two-phase structure.

The weldability is good; electrodes of Kh25N20 steel.

Steel OKh18N10 (OKh18N9, EYa0). The temperature range of hot working is 1150-820°; air cooling.

Standard heat treatment: quenching from 1000-1050° in air or water.

The weldability is satisfactory; electrodes of steel OKh18N9 and Kh18N11B. Quenching is necessary after welding.

Steel Kh18N9 (1Kh18N9, EYa1). The temperature of hot working is 1200-820°; air cooling.

Standard heat treatment: quenching from 1050-1100° in water.

The weldability is satisfactory; electrodes of steel OKh18N9 and Kh18N11B. Quenching is necessary after welding.

Steel OKh18N10T (E1914). Standard heat treatment: quenching from a temperature of 1050-1100° in air, oil, or water.

The weldability is good. This steel is characterized by a higher resistance than steels Kh18N10T and Kh18N12T to intercrystalline corrosion.

Steels Kh18N10T, Kh18N9T (1Kh18N9T, EYa1T), and Kh18N12T. The temperature range of hot working is 1150-850°; air cooling; the pressworkability is good; deep drawing is permitted. These steels are characterized by high ductility in the heat treated state.

Standard heat treatment: quenching from 1050--1100° in air, oil, or water.

The steels lend themselves well to electric arc and automatic welding under a layer of flux. Welding of these steels is carried out with electrodes of austenitic chromium-nickel wire of brands sv. 0Kh18N9, sv. 1Kh18N9B, sv. Kh18N11M, sv. Kh25N13, and others, with coatings UONI-13/NZh, KTI-5, NII-48, TsT-7, and others designed for austenitic electrodes. The resistance of the welded joint to intercrystalline corrosion is satisfactory. The steel does not require compulsory heat treatment after welding.

Steel 4Kh18N25S2 (Kh18N25S2, EYa3S). Standard heat treatment: quenching from 1000° in water. Welds satisfactorily by arc welding; electrode type EA-2S2; electrode material sv. 10Kh20N15.

Steel Kh23N18 (E1417). The temperature range of hot working is 1150-820°; air cooling.

Standard heat treatment: quenching from 1050-1100° in water. In the heat treated state this steel possesses high ductility, and permits deep drawing and other forms of cold pressworking. Tends toward embrittlement in the 600-800° temperature range. Possesses a stable austenitic structure.

The weldability is good; electrode type Ea-2; welding wire of steel of brands sv. 07Kh25N13 or Kh25N20 is recommended.

Steel Kh25N20S2 (E1283). The temperature range of hot working is 1150-820°; air cooling.

Standard heat treatment: quenching from 1050-1100° in water.

The steel welds satisfactorily with the use of electrodes approximating the parent metal in composition.

Steel Kh25N16GAR (E1835). Delivered in the form of thin sheets. Satisfactory pressworkability.

Steel 1Kh25N25TR (E1813). Standard heat treatment: quenching from 1100-1200° in air. Produced in the form of thin sheets. The weldability and pressworkability are satisfactory.

Forms Of Semiproducts And Basic Purpose Of Oxidation-Resistant Steels

The forms of semiproducts of oxidation-resistant steels and the standards for delivered output are given in Table 12, and the application of oxidation-resistant steels, the temperature of the beginning of scale formation, and the operating temperature in Table 13.

Of great importance for the operating characteristics of scale-resistant steels and alloys is their high-temperature strength, that is, their capacity to resist mechanical loads at high temperatures.

The basic estimated characteristics of the high-temperature strength of a metal are the yield point and stress-rupture strength.

The yield point determines the capacity of a metal to resist plastic flow, and the stress-rupture strength the capacity of the metal to resist mechanical failure under the protracted application of a constant load.

Questions of the theory of high-temperature strength, as well as of the properties and application of high-temperature steels and alloys, are widely discussed in numerous literary sources /16, 22, 23, 25, 36, 41, 49, 51, 55/ and are not cited in this handbook.

Oxidation Kinetics

In selecting an oxidation-resistant material it is very important to know the law of development of the oxidation process in time under the conditions of a given atmosphere, or the kinetic equation which would link together the basic parameters determining the rate of scale formation (time, temperature, atmosphere, content of alloying element, etc). No less important is knowledge of the temperature dependence of the oxidation process of a steel or alloy, the composition and structure of the scale, and the distribution of the alloying elements in the latter.

Unfortunately, far from all oxidation-resistant steels and alloys have been subjected to study in this direction. At the present time, sufficient data are not available on the oxidation kinetics in the various aggressive media of steels and alloys designed for operation at high temperatures.

Among the oxidation-resistant steels and alloys enumerated, the greatest amount of study has been devoted to the oxidation kinetics of individual groups of chromium, chromium-nickel, and chromium-aluminum steels and alloys in certain gaseous atmospheres. Concise information on these steels is given below. A description of the oxidation kinetics of alloys is given in Section 2, page .

Chromium steels. Table 14 gives an enumeration of the group of chromium steels, the oxidation kinetics of which have been studied in water vapor at various temperatures.

The curves characterizing the oxidation rate of these steels are given in Figures 19-22, from which it is to be seen that:

(1) the oxidation in time of chromium steels containing from 6 to 31% chromium in water vapor within the 550-1300° temperature range follows the parabolic law;

(2) the oxidation rate decreases with increase in the chromium content.

Microscopic, chemical, and X-ray diffraction analyses of the scale formed on chromium steels containing 6, 13, 16, and 30% Cr in an atmosphere of water vapor at high temperatures have established the following [39].

The scale on steels containing 6 and 13% Cr has three layers: an outer layer, magnetite (Fe_3O_4); a middle layer, Wüstite (FeO); and an inner layer consisting of Wüstite and inclusions of chromium spinel ($FeO + R_3O_4$). The quantitative expression for the composition of the scale of these steels is shown in Figures 23 and 24. The Wüstite phase, FeO, decreases with lowering of the temperature and increase in the chromium content. As a matter of fact, in steel containing 16% Cr, the scale has no Wüstite layer (Fig. 25). The outer and middle layers of the scale (Fe_3O_4 and FeO) in 6 and 13% chromium steel contain no chromium. The chromium is concentrated in the inner scale layer, which consists of Wüstite and chromium spinel.

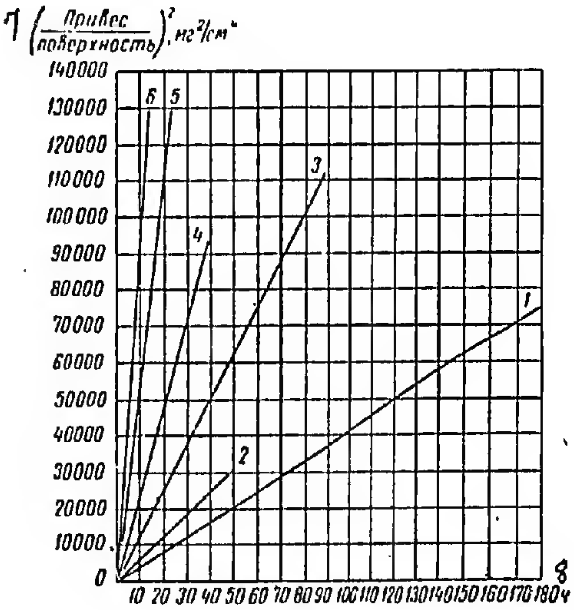


Fig. 19. Kinetics of oxidation of chromium steel containing 5.82% Cr in water vapor [39]:

1 - at 500°;
2 - at 800°;
3 - at 840°;
4 - at 900°;
5 - at 960°;
6 - at 1000°;
7 - (weight gain / surface), mg²/cm⁴;
8 - hours.

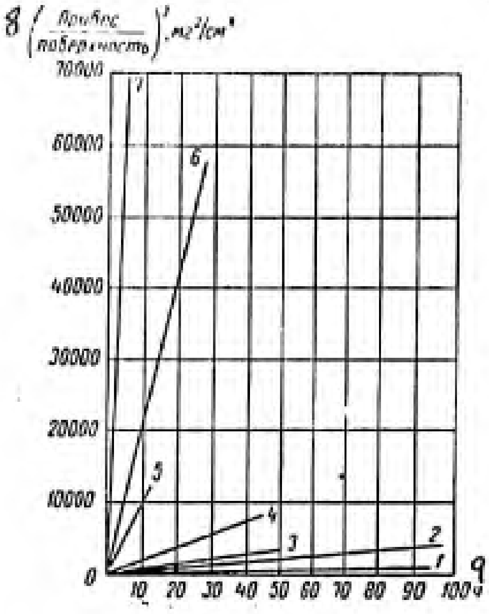


Fig. 20. Kinetics of oxidation of chromium steel containing 12.65% Cr in water vapor [39]:

1 - at 800°;
2 - at 820°;
3 - at 850°;
4 - at 900°;
5 - at 950°;
6 - at 1000°;
7 - at 1050°;
8 - (weight gain / surface), mg²/cm⁴;
9 - hours.

Table 12

Forms Of Semiproducts Of High-Temperature Steels And Standards For Delivered Output

Brand Of Steel Марка стали	Rods Прутки	Strips Полосы	Sections Профили	Pipes Трубы	Forged Pieces Поковки	Sheets Листы	Bands Ленты	Wire Проволока	Castings Отливки	Merchant shapes Сортовой прокат
Х5 Kh5	ГОСТ 5949—61	ГОСТ 5949—61	—	ГОСТ 550—58	—	—	—	—	—	—
4Х9С2 (Х9С2, ЭСХ8) 4Kh9S2(Kh9S2, ESKh8)	ГОСТ 5949—61 МПТУ 4416—54	ГОСТ 5949—61 ЧМТУ 2913—51	—	—	—	—	—	—	—	ЧМТУ 2913—51
4Х10С2М (Х10С2М, ЭИ107) 4Kh10S2M (Kh10S2M, EI107)	ГОСТ 5949—61 МПТУ 2352—49 МПТУ 2420—49 МПТУ 2399—49	ГОСТ 5949—61 МПТУ 2362—49	—	—	МПТУ 2332—49		—	—	—	МПТУ 2362—49 МПТУ 2420—49 ЧМТУ 2913—51
3Х13Н7С2 (ЭИ72, Х13Н7С2) 3Kh13N7S2 (EI72, Kh13N7S2)	ГОСТ 5949—61	ГОСТ 5949—61	—	—	—	—	—	—	—	—
Х6СЮ (ЭИ428) Kh6SYu (EI428)	ГОСТ 5949—61	ГОСТ 5949—61	—	—	—	—	—	—	—	—
1Х13 (ЭЖ1) 1Kh13 (EZh1)	ГОСТ 5919—61 МПТУ 2362—49 МПТУ 3290—53 МПТУ 2188—49 ГОСТ 2588—44 МПТУ 2420—49 ЧМТУ 3536—53	ГОСТ 5919—61 МПТУ 2362—49 (1) Нормаль Ст. 1392к	—	ЧМТУ 3231—52 $\frac{\text{ЧМТУ}}{\text{ВНИТИ}}$ 31—58	—	ГОСТ 5582—61 ЧМТУ 3126—52 МПТУ 2495—50 ГОСТ 7350—55 (2) Нормаль Ст. 1392к	ГОСТ 4986—54	ГОСТ 5518—50 ТУС 137 — 6027—54 ЧМТУ 5195—55	(3) Нормаль Ст. 1391к Заготовки для лопаток и заклепок паровых турбин	ГОСТ 5949—61 МПТУ 2362—49 МПТУ 2420—49 МПТУ 3290—52
Х17 (ЭЖ17) Kh17 (EZh17)	ГОСТ 5949—61	ГОСТ 5949—61	—	ГОСТ 9940—62, ГОСТ 9941—62 ЧМТУ 4875—54	—	ГОСТ 5582—61 ГОСТ 7350—55	—	ГОСТ 5548—50	—	—
0Х17Т (ЭИ645) 0Kh17T (EI645)	ГОСТ 5949—61	ГОСТ 5949—61	—	—	—	ГОСТ 7350—55 ГОСТ 5582—61	—	—	—	—
Х18СЮ (ЭИ484) Kh18SYu (EI484)	ГОСТ 5949—61	ГОСТ 5949—61	—	—	—	—	—	—	—	—
Х25Т (ЭИ439) Kh25T (EI439)	ГОСТ 5949—61	ГОСТ 5949—61	—	ГОСТ 9940—62, ГОСТ 9941—62 ЧМТУ 4875—54	—	ГОСТ 5582—61	—	—	—	—
Х28 (ЭЖ27, ЭИ349) Kh28 (EZh27, EI349)	ГОСТ 5949—61	ГОСТ 5949—61	—	ГОСТ 5543—50 ЧМТУ 4875—54	—	ГОСТ 5582—61	—	ГОСТ 5548—50	ГОСТ 2176—57	—
0Kh20N14S2 (EI732) 0Х20Н14С2 (ЭИ732)	ГОСТ 5949—61	ГОСТ 5949—61	—	—	—	—	—	—	—	—
Х20Н14С2 (ЭИ211) Kh20N14S2 (EI211)	ГОСТ 5949—61	ГОСТ 5949—61	—	—	—	ГОСТ 5582—61	—	ГОСТ 5548—50	—	—

Table 12 (Cont'd)

Продолжение табл. 12

Brand of steel Марка стали	Rods Прутки	strips Полосы	Sections Профили	Pipes Трубы	Forged pieces Поковки	sheets Листы	Bands Ленты	Wire Проволока	Castings Отливки	Merchant shapes Сортовой прокат
X23H13 (ЭИ319) Kh23N13 (EI 319)	ГОСТ 5949—61	ГОСТ 5949—61	—	—	—	ГОСТ 7350—55	—	ГОСТ 5548—50	—	ГОСТ 5949—61 МПТУ 2362—49
0X18H10 (0X18H9, ЭЯ0) OKh18N10 (OKh18N9, EYa0)	ГОСГ 5949—61	ГОСТ 5949—61	—	ЧМТУ 4871—54	—	ГОСТ 5582—61 ЧМТУ 3126—52 ГОСТ 7350—55	ГОСТ 4986—54	ГОСТ 5548—50	—	—
X18H9 (1X18H9, ЭЯ1) Kh18N9 (1Kh18N9, EYa1)	ГОСТ 5949—61	ГОСТ 5949—61	—	ГОСТ 9940—62, ГОСТ 9941—62	—	ГОСТ 5582—61 ГОСТ 7350—55	—	—	—	—
0X18H10T (ЭИ914) OKh18N10T (EI914)	ГОСТ 5949—61	ГОСТ 5949—61	—	—	—	ГОСТ 5582—61	—	—	—	—
X18H10T (1X18H9T, ЭЯ1T) Kh18N10T (1Kh18N9T, EYa1T)	ГОСТ 5949—61 МПТУ 2352—49 ЧМТУ 3293—53 ГОСТ 2588—44 МПТУ 2399—49	ГОСТ 5949—61 МПТУ 2362—49	ЧМТУ 5336—55 АМТУ 361—56 (4) Гильзы $\frac{\text{ЧМТУ}}{\text{ВНИТИ}}$ 13—58	ГОСТ 5543—50 ЧМТУ 4875—54 ЧМТУ 4870—51 ЧМТУ 3803—53 МПТУ 4384—54 МПТУ 4408—54 МПТУ 4089—55 ЧМТУ 5288—55 ЧМТУ 5536—56 ЧМТУ 2850—51 ЧМТУ 2884—51 ЧМТУ 2885—51 $\frac{\text{ЧМТУ}}{\text{ВНИТИ}}$ 21—58 и 40—58 and	(5) Поковки деталей турбомашин ТУ (заводские)	ГОСТ 5582—61 ЧМТУ 3126—52 ГОСТ 7350—55 МПТУ 2495—50 ЧМТУ 5392—56 ЧМТУ 2896—51 ЧМТУ 2780—51 ЧМТУ 2751—51 ЧМТУ 3366—53 ЧМТУ 4552—54 ЧМТУ 4551—54 ЧМТУ 4767—54 ЧМТУ 3396—53	ГОСТ 4986—54 ЧМТУ 5350—53	ГОСТ 5548—50 ЧМТУ 4835—54	—	ГОСТ 5949—61 МПТУ 2362—49 ЧМТУ 3290—51
X18H9T (1X18H9T, ЭЯ1T) Kh18N9T (1Kh18N9T, EYa1T)	ГОСТ 5949—61	ГОСТ 5949—61	—	—	—	—	—	—	—	—
X18H12T Kh18N12T	ГОСТ 5949—61	ГОСТ 5949—61	—	—	—	ГОСТ 5582—61	—	—	—	—
4X18H25C2 (X18H25C2, ЭЯ3С) 4Kh18N25S2 (Kh18N25S2, EYa3S)	ГОСТ 5949—61	ГОСТ 5949—61	—	—	—	—	—	—	—	—
X23H18 (ЭИ417) Kh23N18 (EI 417)	ГОСТ 5949—61 МПТУ 2362—49	ГОСТ 5949—61 МПТУ 2362—49	АМТУ 361—56	ЧМТУ 4720—54	—	ГОСТ 5582—61 ЧМТУ 3126—52 ГОСТ 7350—55 ЧМТУ 4551—54 ЧМТУ 4552—54	ГОСТ 4986—54	ГОСТ 5548—50	—	ГОСТ 5949—61 МПТУ 2362—49
X25H16Г7AP (ЭИ835) Kh25N16G7AR (EI835)	ГОСТ 5949—61	ГОСТ 5949—61	—	—	—	ГОСТ 5582—61	—	—	—	—
X25H20C2 (ЭИ283) Kh25N20S2 (EI283)	ГОСТ 5949—61	ГОСТ 5949—61	—	—	—	ГОСТ 5582—61	—	—	—	—
1X25H25TP (ЭИ813) 1Kh25N25TR (EI 813)	ГОСТ 5949—61	ГОСТ 5949—61	—	—	—	ГОСТ 5582—61 ЧМТУ 5831—57	—	—	—	—

Translation of terms used on Table 12 follows:

ГОСТ = GOST (All-Union State Standard;

МПТУ = MPTU (specifications;

ЧМТУ = ChMTU (Ferrous Metallurgy Technical Specifications);

ВНИТИ = VNITI;

(1) Standard St. 1392k; (2) Standard St. 1392k; (3) Standard St. 1391K, blanks for blades and rivets of steam turbines; (4) Sleeves; (5) Forged pieces for parts of turbodynamos; Technical Specifications (plant).

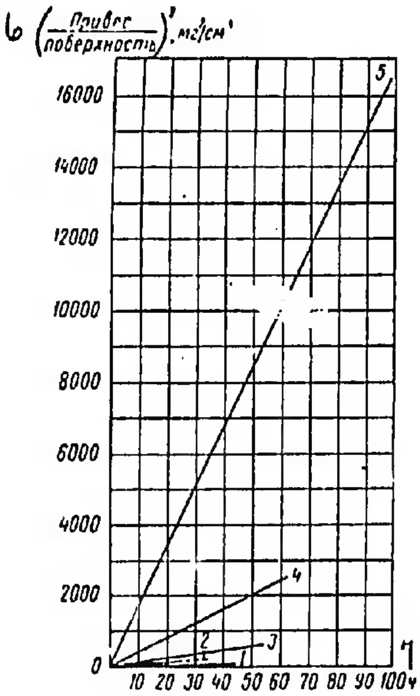


Fig. 21. Kinetics of oxidation of chromium steel containing 16% Cr in water vapor [39]:

(1) at 800°;
(2) at 880°;
(3) at 900°;
(4) at 950°;
(5) at 1000°;
(6) $\left(\frac{\text{weight gain}}{\text{surface}}\right)$, mg^2/cm^4;
(7) hours.

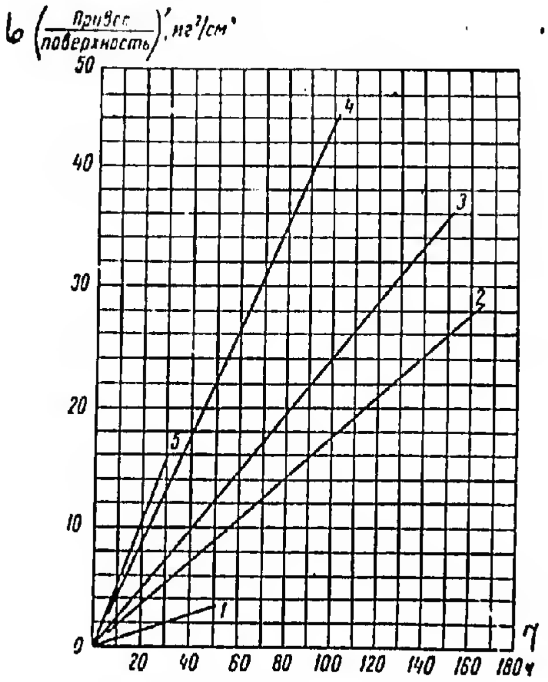


Fig. 22. Kinetics of oxidation of chromium steel containing 31.3% Cr in water vapor [39]:

(1) at 1000°;
(2) at 1080°;
(3) at 1120°;
(4) at 1200°;
(5) at 1300°;
(6) $\left(\frac{\text{weight gain}}{\text{surface}}\right)$, mg^2/ cm^4;
(7) hours.

Table 13

Basic Purpose Of Oxidation-Resistant Steels (GOST 5632-61) [45, 51]

Brand of Steel	Temperature of beginning of scale formation in air, °C	Operating temperature. Special properties	Basic Purpose
Kh5	600--650	Operating temperature 600°	Pipes
4Kh9S2 (Kh9S2, ESKh8)	800-850	Operating temperature in long service in slightly loaded state up to 700-800°. Stable in media containing sulfur	Valves of automobile, tractor, and diesel motors; pipes of regenerators, heat exchangers, gratings, etc.
4Kh10S2M (Kh10S2M, E1107)	850-900	Satisfactory stability of mechanical properties up to 500°. Above this temperature the stress-rupture strength, creep, and impact toughness decrease sharply with lengthy holding. Operating temperature 450-500° in protracted operation. Stable in media containing sulfur.	Exhaust valves of piston engines of medium and high power; exhaust valves of high-speed diesels, fastenings of motors.
3Kh13N7S2 (Kh13N7S2, E172)	900-950	Operating temperature up to 850-950°. The most highly oxidation-resistant steel of the brands of silichromes. Stable in atmospheres containing sulfur.	Valves of high-power motors.

Table 13 (Cont'd)

Brand of Steel	Temperature of beginning of scale formation in air, °C	Operating temperature. Special properties	Basic Purpose
Kh6SYu (E1428)	800	Operating temperature in the unloaded state up to 750°. Low mechanical strength at high temperatures. Stable in media containing sulfur.	Pipes, parts of boiler installations.
1Kh12SYu (Kh12YuS, E1404)	900-950	Operating temperature in loaded state up to 850°. Low mechanical strength at high temperatures. Stable in media containing sulfur.	Valves of tractor motors.
Kh18SYu E1484)	1050	Operating temperature in unloaded state up to 1000° Low mechanical strength at high temperatures. Stable in media containing sulfur.	Pipes and apparatus of pyrolysis assemblies.
1Kh13 (EZh1)	700-750	Operating temperature 400-450°; high damping decrement under slight stresses up to 550°. Low sensitivity to concentrations of stresses in the 470-530° temperature range. Stability of mechanical properties up to 550°.	Turbine blades, steel-tire strips, valves of hydraulic presses, parts of water pumps and carburetors; fittings of cracking plants, fastenings, pipes, boiler parts.

Table 13 (Cont'd)

Brand of Steel	Temperature of beginning of scale formation in air, $^{\circ}C$	Operating temperature. Special properties	Basic Purpose
Kh17 (EZh17)	850--900	Steels Kh17 and Kh28 are employed predominantly as stainless steels. The strength properties decrease sharply at temperatures above 400°. They tend toward grain growth and brittleness. Steel Kh28 is used for parts operating in an unloaded state in gaseous atmospheres at temperatures up to 1100°.	Equipment of nitric acid and canning plants; absorption towers, heat exchangers for hot nitrose gases and hot nitric acid. Tanks for acids, pipes, pipelines.
Kh28 (EZh27, E1349)	1100-1150		Pipes of pyrolysis assemblies, heat exchangers, Apparatus operating in solutions of sodium hypochlorite, fuming nitric or phosphoric acid
OKh17T (E1645)	900	Steels OKh17T and Kh25T are used for the manufacture of welded structures not subjected to the action of impact loads at operating temperatures below -20°. The steels possess a high resistivity to intercrystalline corrosion compared to high-chromium steels not alloyed with titanium. Steel Kh25 is stable toward the action of sulfur gases.	Equipment of food industry plants. Pipes, heat exchangers.
Kh25T (E 439)	1000-1050		Covers of thermocouples, electrodes of spark ignition plugs, pipes of pyrolysis assemblies, heat exchangers. Chemical apparatus.

Table 13 (Cont'd)

Brand of Steel	Temperature of beginning of scale formation in air, °C	Operating temperature. Special properties	Basic Purpose
OKh20N14S2 (E1732)	1000-1050	Low-high-temperature strength. Operating temperature in unloaded or slightly loaded state up to 1000°. Stable in carburizing atmospheres.	Pipes.
Kh20N14S2 (E1211)	1000-1050		Hangers and supports in boilers, furnace conveyors, carburizing containers.
4Kh18N25S2 (Kh18N25S2, EYa3S)	1000-1100	Operating temperature in unloaded state 1000-1100°. The steel possesses high mechanical properties up to 800°, but low impact toughness at room temperature. Stable in carburizing atmospheres.	Furnace conveyors and other parts.
Kh25N20S2 (E1283)	1100-1150	Low high-temperature strength. Operating tenperature for unloaded and slightly loaded parts up to 1000-1050°. In the 600--800° temperature range tends toward embrittlement due to formation of the sigma phase.	Hangers and supports in boilers, electrolysis and pyrolysis assemblies, furnace conveyors, carburizing containers, fastenings subjected to high temperatures and pressures.

Table 13 (Cont'd)

Brand of Steel	Temperature of beginning of scale formation in air, °C	Operating temperature. Special properties	Basic Purpose
OKh18N10 (OKh18N9, EYa0)	800	Steels OKh18N10 and Kh18N9 are employed chiefly as corrosion-resistant steels. They are characterized by high corrosion resistance in aggressive atmospheres.	Parts manufactured by deep drawing, welding wires for welding of chromium-nickel steels of the 1Kh18N9T type.
Kh18N9 (1Kh18N9, EYa1)	800	Tend toward intercrystalline corrosion.	Aircraft parts, seaplane floats, pipes, Material for decorative finishing of buildings. Non-magnetic parts of ship control apparatus.
OKh18N10T (E1914)	800	Steels OKh18N10T, Kh18N10T, and Kh18N12T are characterized by satisfactory high-temperature strength up to 550-600° and mechanical properties of high stability up to 600° for 5,000-10,000 hours. The steels are designed for superheater pipes of long service life at an operating temperature of 600°. Unstable in atmospheres containing sulfur.	Furnace fitting parts, heat exchangers, mufflers retorts, sleeves and collectors of exhaust systems, electrodes of spark ignition plugs, pipes, chemical industry welded apparatus.
Kh18N10T, (1Kh18N9T, EYa1T)	800		
Kh18N12T	800-850		Pipes, parts of exhaust systems.

Table 13 (Cont'd)

Brand of Steel	Temperature of beginning of scale formation in air, °C	Operating temperature. Special properties	Basic Purpose
Kh23N13 (E1319)	1000-1050	Maximum operating temperature in the unloaded state 550°; under sligh stresses 650-700°; may be employed at up to 900-1000° in unloaded state due to high oxidation resistance. Tends toward embrittlement in the 600--800° temperature range due to formation of the sigma phase.	Pipes for pyrolysis of methane, pyrometric pipes, flues of combustion chambers of mobile and stationary gas turbines, welding wire.
0Kh23N18, Kh23N18	1050	Operating temperature for parts in unloaded state 900-1000°. Mechanical properties low in 500-700° temperature range. When the steel is at 800° for a brief period, its impact toughness is cut in half. The steels are employed chiefly for parts operating in the unloaded state or under a stress of 1-2 kg/mm^2. The steels are unstable from the structural standpoint. In the 600-800° temperature range, they tend toward embrittlement due to formation of the sigma phase.	Flues and other parts of combustion chambers, guide apparatus of gas turbines; parts of plants for conversion of methane, pyrolysis of gases and hydrogenation; for the manufacture of sheet-like parts.

Table 13 (Cont'd)

Brand of Steel	Temperature of beginning of scale formation in air, °C	Operating temperature. Special properties	Basic Purpose
Kh25N16G7AR (E1835)	1050-1100	Oxidation-resistant at up to 1000°. Low high-temperature strength.	Parts of gas pipeline systems manufactured from thin sheets, strips, and merchant shapes.
1Kh25N25TR (E1813)	1100	Oxidation resistance of the steel: at 800° weight gain of 0.01 $g/m^2 \cdot h$ in 1000 h; at 1000° weight gain of 0.025 $g/m^2 \cdot h$ in 100 h; at 1100° weight gain of 0.036 $g/m^2 \cdot h$ in 100 h. The steel is designed for slightly loaded parts operating at up to 1000°.	Combustion chambers of gas turbines and other parts manufactured from sheets for gas pipeline systems.

In the outer layer of the scale of 16% chromium steel, there is always a certain amount of chromium.

The composition of the scale of 30% chromium steel differs fundamentally from the scale on steels having a lower chromium content. The scale of 30% chromium steel is in one layer and consists of the phase R_2O_3, which approximates Cr_2O_3 in composition.

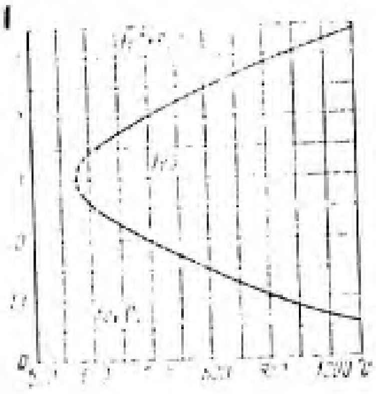


Fig. 23. Composition of scale on chromium steel containing 5.8% Cr, after tests in water vapor at various temperatures [39]: 1 - Scale composition, %.

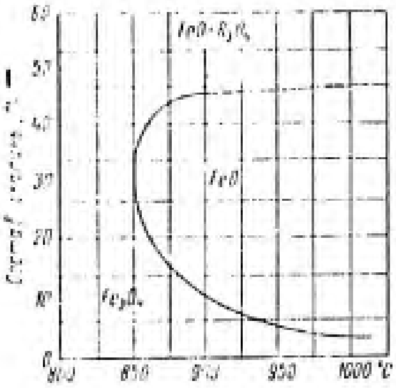


Fig. 24. Composition of scale on chromium steel containing 12.65% Cr, after tests in water vapor at various temperatures [39]: 1 - Scale composition, %.

The pattern of oxidation of the metal may vary in accordance with the composition of the gaseous atmosphere, the temperature, and the heating period. Thus, V. V. Ipat'yev [40] has found that the oxidation of steel 1Kh13 in air at 850-1050° is characterized by an initial, so-called induction period, during which the rate of scale formation is very low. This period is the longer, the lower is the temperature (Fig. 26). Thus, at 1050° it equals approximately two hours, and at 850° ____ hour(s). During the induction period, the oxidation of steel 1Kh13 follows the logarithmic law, and subsequently, the parabolic law.

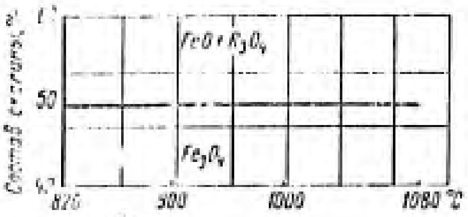


Fig. 25. Composition of scale on 16% chromium steel after tests in water vapor at various temperatures 39 : 1 - Scale composition, %.

Table 14

Kinetics of Oxidation Of Chromium Steels In Water Vapor [39]

1 Марка стали	2 Содержание хрома в исследуемой стали, %	3 Температурный интервал, °C	4 Продолжительность испытаний, ч
X5	5,82	550—1000	20—351
1X13 (ЭЖ1)	12,65	700—1050	5,5—425
X17 (ЭЖ17)	16,0	780—1000	14—307
X28 (ЭЖ27)	31,3	1000—1300	33—163

1 - Brand of steel; 2 - Chromium content of steel under study, %; 3 - Temperature range, °C; 4 - Test period, h.

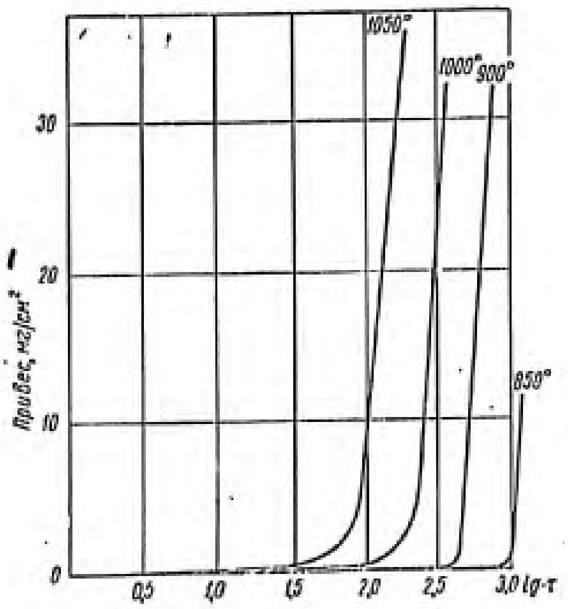


Fig. 26. Induction period versus temperature in oxidation of 1Kh13 steel in air [40]: 1 - weight gain, mg/cm^2.

The kinetics of oxidation of 1Kh13 steel in air at various temperatures is shown in Fig. 27, from which it is to be seen that the curves are the same in nature: each curve has a rectilinear section characterizing the rate of oxidation of the steel according to the parabolic law and a section with a slower rate attesting to change in the oxidation pattern of the steel during the initial period.

The oxidation of chromium steel Kh17 in air at 1100° with short exposures also follows the logarithmic law (Fig. 28), which with a period $\tau < 40$ min is determined by the empirical equation $\Delta g = 78 \lg\tau - 46$, and for $\tau > 40$ min by the expression $\Delta g = 9.6 \lg\tau + 67$.

The slower rate of oxidation of chromium steels in the initial state, as has been shown by chemical, metallographic, and X-ray diffraction analyses, is explained by the formation on the surface of the metal of a very thin film of the R_2O_3 type, the chromium content of which is considerably higher than in the initial steel [40].

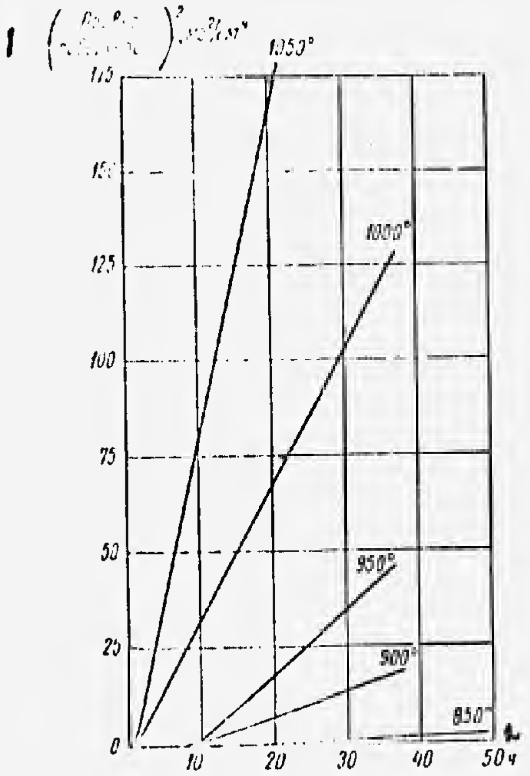


Fig. 27. Kinetics of oxidation of chromium steel 1Kh13 in air at various temperatures [40]:

1 - ($\frac{\text{weight gain}}{\text{surface}}$), mg^2/cm^4;

2 - hours.

Fig. 28. Kinetics of oxidation of steel Kh17 in air at 1100° [18]: 1 - Weight gain, g/m^2; 2 - hours.

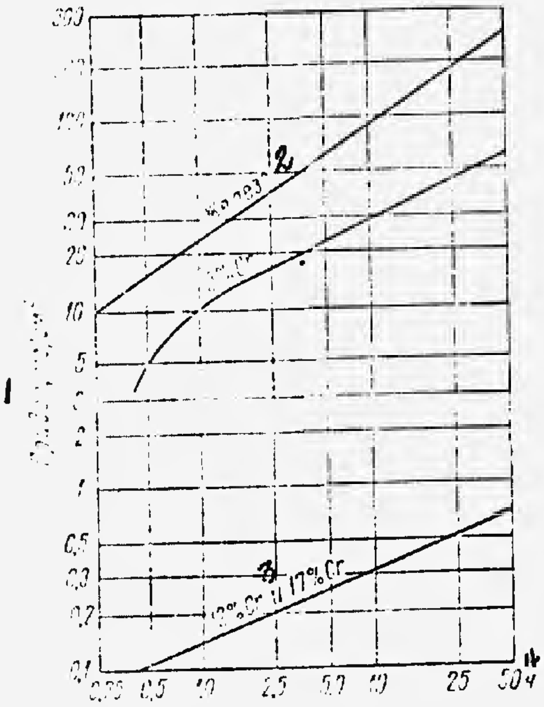


Fig. 29. Kinetics of oxidation of iron and chromium steels at a temperature of 900° in air [66]: 1 - Weight gain, mg/cm^2;

2 - Iron

3 - And.

4 - Hours

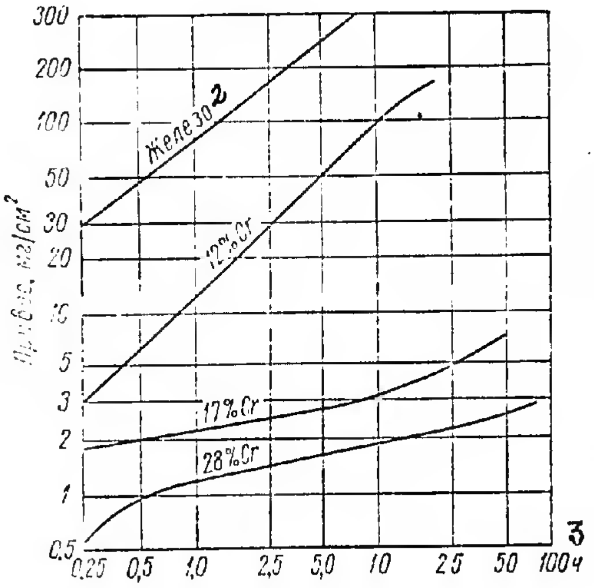


Fig. 30. Kinetics of oxidation of iron and chromium steels in air at 1100° [66]:

1 - Weight gain, mg/cm²;

2 - Iron

3 - Hours.

The kinetics of oxidation of the group of chromium steels in air at 900 and 1100° as compared with iron is shown in Figures 29 and 30, from which it is to be seen that with increase in the chromium content of the steel, the oxidizability of the latter is retarded in time. This is manifested with particular clarity at 1100°. At temperatures up to 900° chromium steels containing 12-17% Cr are sufficiently oxidation-resistant, and steels containing 17-28% Cr are so at 1100°.

Chromium-nickel steels. The chromium-nickel steels,t the oxidation kinetics of which has been studied in certain gaseous media are given in Table 15.

Table 15

Oxidation Kinetics Of Certain Brands Of

Chromium-Nickel Steels [1, 32, 45]

Brand of steel	Gaseous medium	Temperature, °C	Test period, h
Kh18N9 (EYa1)	Air Furnace atmosphere α = 0.8; 1.0; 1.2	1100 1100	From 0.5 to 100 20 min*
1Kh18N9T (EYa1T)	Superheated steam Air	600 1100	600 5
Kh23N13 (E1319)	Air	1100	From 0.5 to 100
Kh23N18 (E1417)	Furnace atmosphere: α = 0.8; 1.0; 1.2	1000	20 min*
Kh25N16G7AR (E1835)	Air	900-1200	1
Kh25N25TR (E1813)	Furnace atmosphere: α = 0.8 and 1.5	900-1200	1

---

*Technological holding for rolling.

Given in Fig. 31 are curves of oxidation of steels Kh18N9 and Kh23N13 in time at 1100° in air, from which it is to be seen that the rate of oxidation of steel Kh18N9, after a certain increase during the initial period, subsequently slows down and increases sharply after 100 hours of holding.

The nature of the oxidizability of steel Kh23N13 differs: with holding for up to 15 hours, the oxidation rate increases continuously, then slows down.

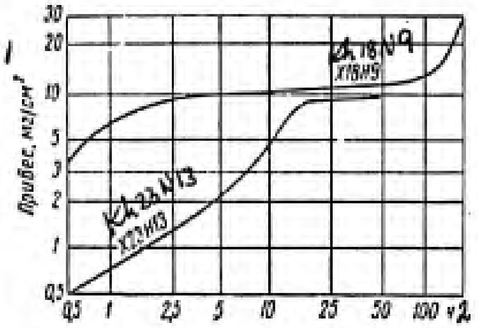


Fig. 31. Kinetics of oxidation of chromium-nickel steels Kh18N9 and Kh23N13 in air at 1100° [66]:

1 - Weight gain, mg/cm^2;

2 - Hours.

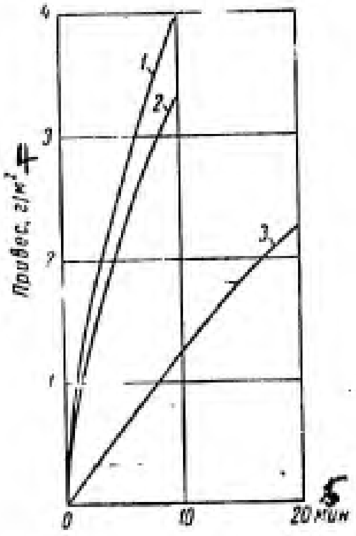


Fig. 32. Kinetics of oxidation of chromium-nickel steel Kh18N9 in reducing, neutral, and oxidizing furnace atmospheres at 1000° [32]:

1 - = 0.8;

2 - = 1.0;

3 - = 1.2;

4 - Weight gain, g/m^2;

5 - Minutes.

Figures 32 and 33 show the kinetics of steel Kh18N9 and Kh23N18 in reducing, neutral, and oxidizing furnace atmospheres (the excess air coefficient is respectively 0.8, 1.0, and 1.2) at 1000°. The test period corresponds to technological holding of the steels in heating for rolling. The oxidation of steels Kh18N9 and Kh23n18 with time, as may be seen from Table 16, in all three atmospheres follows the logarithmic law

$$\Delta g = k_1 \tau \lg + k_2,$$

where k_2 is the weight gain Δg at $\tau = 1$;

k_1 is the tangent of the angle of inclination of the line to the X-axis.

With steels and alloys oxidizing in time according to the logarithmic law, constant k_2 is a characteristic of the protective properties of the initial oxide film formed under the given conditions, and k_1 characterizes the change in the protective properties of the film in time during the subsequent growth of the film.

Equations of oxidation of steels Kh18N9 and Kh23N18 for various atmospheres are given in Table 16.

It is to be seen from comparison of the oxidation curves of both brands of chromium-nickel steels that with steel Kh23N18, which has a higher chromium content, the protective properties of the oxide film are higher than with steel Kh18N9. This is explained by the structure of the oxide films, which with both steels represents spinel of the $FeO \cdot Cr_2O_3$ type, except that for steel Kh23N18, the steel contains a larger quantity of Cr_2O_3 as compared with the oxides on steel Kh18N9 [32].

Curves of the oxidation of steel 1Kh18N9T in superheated steam at 600° and in air at 1100° are shown in Figures 34 and 35. The oxidation of steel 1Kh18N9T in the atmospheres in question follows the logarithmic law.

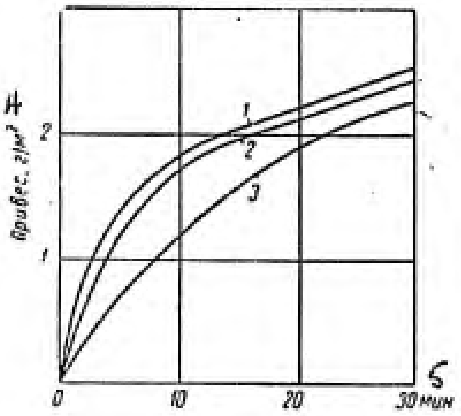


Fig. 33. Kinetics of oxidation of chromium-nickel steel Kh23N18 in reducing, neutral, and oxidizing furnace atmospheres at 1000° [32]:
1 - α = 0.8;
2 - α = 1.0;
3 - α = 1.2;
4 - Weight gain, g/m²;
5 - Minutes.

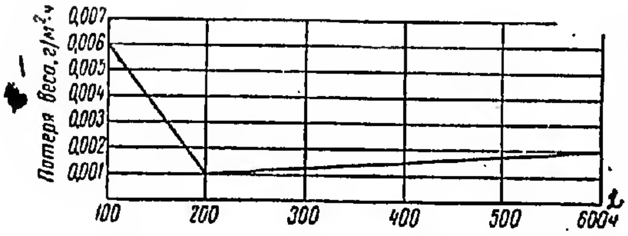


Fig. 34. Kinetics of oxidation of chromium-nickel steel 1Kh18N9T in superheated steam at a temperature of 600° [45]:

1 - Weight loss, g/m² • h;

2 - Hours.

The kinetics of oxidation of steels Kh25N16G7AR (E1835) and Kh25N25TR (E1813) has been studied in the 900-1000° temperature range in air and in a furnace atmosphere with α = 0.8 and 1.5. It has been found that at 900 and 1000°, steel E1835 is distinguished by a high oxidation resistance in the atmospheres investigated. The oxidation resistance of the steel is impaired at temperatures above 1000°(Fig. 36).

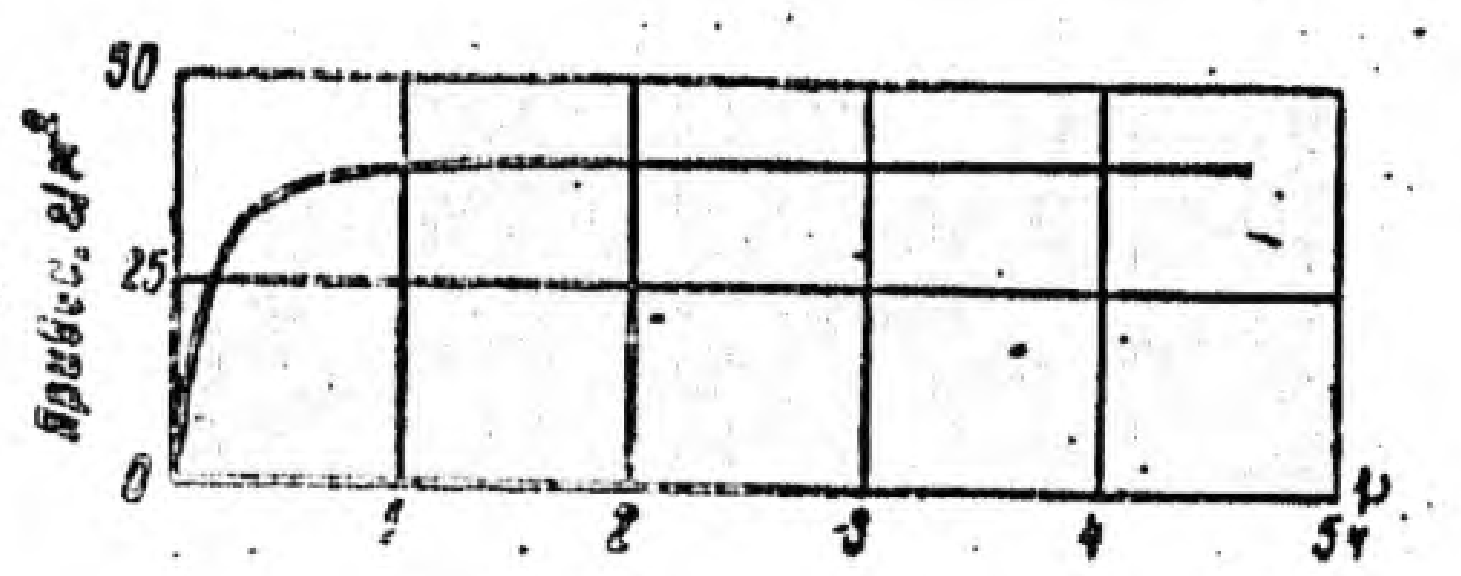


Fig. 35. Kinetics of oxidation of steel 1Kh18N9T in air at 1100° [18] :

1 - Weight gain, g/m^2

2 - Hours.

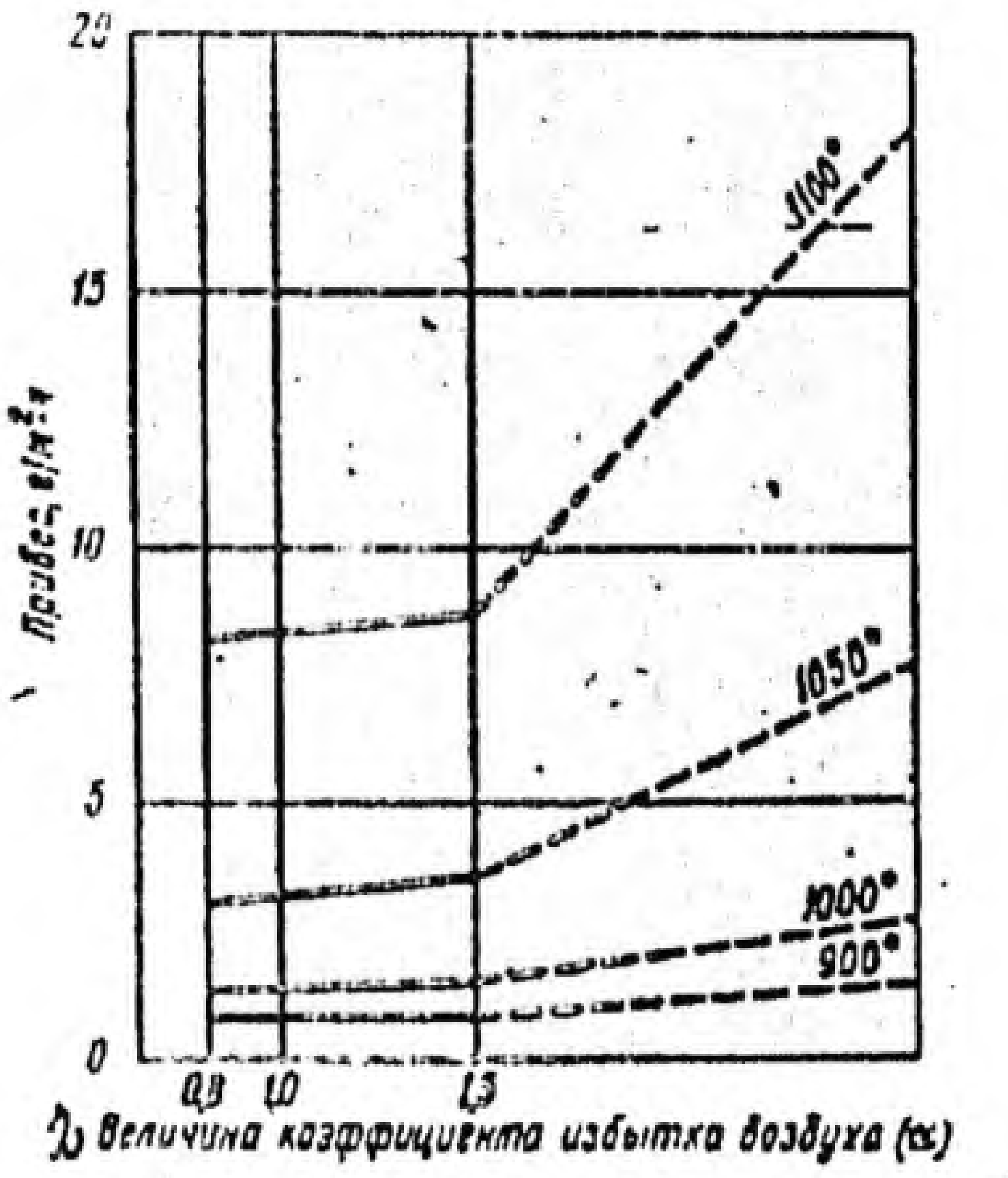


Fig. 36. Kinetics of oxidation of chromium-nickel steel E1835 in air and in a furnace atmosphere at temperatures of 900, 1000, 1050, and 1100° [1] :

1 - Weight gain, g/m^2 · h;

2 - Value of excess air coefficient (α).

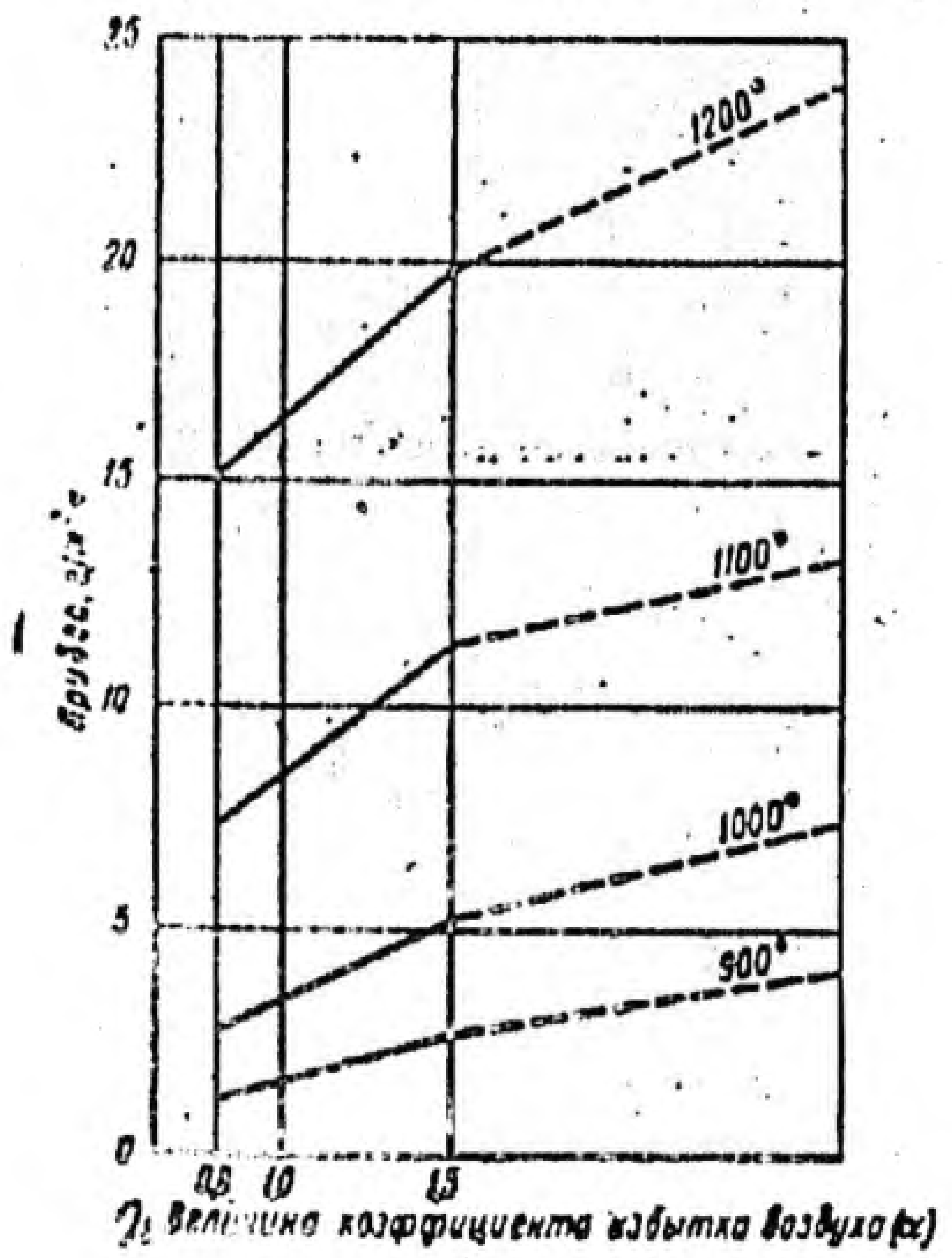


Fig. 37. Kinetics of oxidation of chromium-nickel steel E1813 in air and in a furnace atmosphere within the 900-1200° temperature range [1]:

1 - Weight gain, g/m^2 · h;

2 - Value of excess air coefficient (α).

With increase in the excess air coefficient, α, in a furnace atmosphere, the rate of oxidation of steel E1835 at 900 and 1000° increases somewhat, and at 1050 and 1100° rises sharply on transition to an atmosphere of air. The kinetics of growth of the oxide film follows the logarithmic law (Table 17).

The rate of oxidation of steel E1813 at 900-1200° increases with increase in the excess air coefficient (Fig. 37).

The kinetics of growth of the oxide film in all three atmospheres is described by parabolic equations the indices of which decrease with elevation of the temperature (Table 17).

The average rate of oxidation of steels E1835 and E1813 in one hour is given in Table 18.

Table 16

Equations For Oxidation Of Steels Kh18N9 And Kh23N18 In A Furnace Atmosphere At 1000° [32]

1 Марка стали	2 Коэффициент избытка воздуха α	3 Уравнение окисления $\Delta g = f(\tau)$
Х18Н9 Kh18N9	0,8 1,0 1,2	$\Delta g=4{,}3 \lg \tau - 0{,}25$ $\Delta g=3{,}6 \lg \tau - 0{,}20$ $\Delta g=2{,}7 \lg \tau - 1{,}30$
Х23Н18 Kh23N18	0,8 1,0 1,2	$\Delta g=2{,}0 \lg \tau - 0{,}25$ $\Delta g=2{,}2 \lg \tau - 0{,}65$ $\Delta g=2{,}2 \lg \tau - 1{,}05$

1 - Brand of steel; 2 - Excess air coefficient; 3 - Oxidation equation; Note: Δg -- weight gain, g/m²; τ -- oxidation time, minutes.

Table 17

Oxidation Equations for Steels E1835 and E1813 [1]

$$\Delta g = f(\tau)$$

1 Марка стали	2 Температура °C	3 Воздух	4 Печная атмосфера	
			α = 1,5	α = 0,8
E1835 ЭИ835	900	$\Delta g = 0{,}91 \lg \tau - 0{,}05$	$\Delta g = 0{,}50 \lg \tau + 0{,}10$	$\Delta g = 0{,}33 \lg \tau + 0{,}25$
	1000	$\Delta g = 2{,}30 \lg \tau - 0{,}41$	$\Delta g = \lg \tau$	$\Delta g = 0{,}67 \lg \tau + 0{,}20$
	1100	—	$\Delta g = 4{,}95 \lg \tau + 0{,}20$	$\Delta g = 3{,}89 \lg \tau + 1{,}50$
E1813 ЭИ813	900	$\Delta g^{5,63} = 15{,}14\tau$	$\Delta g^{2,82} = 0{,}19\tau$	$\Delta g^{3,82} = 0{,}02\tau$
	1000	$\Delta g^{2,81} = 3{,}89\tau$	$\Delta g^{2,80} = 1{,}72\tau$	$\Delta g^{2,61} = 0{,}19\tau$
	1100	$\Delta g^{2,44} = 10{,}47\tau$	$\Delta g^{2,14} = 2{,}82\tau$	$\Delta g^{2,61} = 3{,}74\tau$
	1200	$\Delta g^{2,44} = 36{,}3\tau$	$\Delta g^{2,14} = 9{,}22\tau$	$\Delta g^{2,46} = 13{,}5\tau$

1 - Brand of steel; 2 - Temperature, °C; 3 - Air; 4 - Furnace atmosphere.

Table 18

Average Rate of Oxidation of Steels E1835 and E1813 in g/m² . h in τ = 1h [1]

1 Температура °C	2 ЭИ813			3 ЭИ835		
	4 Воздух	5 Печная атмосфера		4 Воздух	5 Печная атмосфера	
		α = 1,5	α = 0,8		α = 1,5	α = 0,8
900	3,80	2,59	1,05	1,65	0,89	0,88
1000	7,12	5,13	2,77	2,56	1,65	1,41
1100	13,18	11,37	7,81	18,2	8,96	8,45
1200	23,37	19,66	14,75	—	—	—

1 - Temperature, °C; 2 - E1813; 3 - E1835; 4 - Air; 5 - Furnace Atmosphere.

Corrosion Resistance in Gaseous Atmospheres

The most widespread steels in industry are chromium and chromium-nickel steels. They are characterized by a higher oxidation resistance in various aggressive atmospheres than are carbon steels. Thus, in an atmosphere of air contaminated with 2% sulfurous acid anhydride, chromium-nickel steel of the Kh18N9 type possesses a resistance to oxidation which is 58 times greater than that of carbon steel; and in ordinary atmosphere one which is 124 times greater. Comparative data on the resistance to oxidation of carbon steel and steel of the Kh18N9 type in various atmospheres are given in Table 19.

Given in Table 20 are comparative data on the oxidizability of chromium and chromium-nickel steels at high temperatures in oxygen, carbon dioxide, and sulfurous acid anhydride. Data on the oxidizability of low-carbon steel is given in the same table for the sake of comparison. The table shows just how effectively the alloying of steel with chromium influences its resistance at high temperatures in an atmosphere of oxygen, carbon dioxide, or sulfurous acid anhydride.

With a chromium content of 13-14% in the steel, the weight gain of the latter in the atmospheres indicated, is virtually negligible in comparison with carbon steel operating at a temperature up to 900°, and up to 1000° for steel containing 18% Cr.

Table 19

Oxidizability Of Carbon Steel And Chromium-Nickel Steel Kh18N9 In Various Atmospheres 8 *

9 Среда	10 Привес, мг/дм²		13 Отношение $\frac{a}{б}$
	11 низкоуглеродистая сталь (a)	12 сталь Х18Н9 (б)	
1 Чистый воздух	5 524	40	138
2 Обычная атмосфера	5 717	46	124
3 Чистый воздух+2% SO_2	6 517	86	76
4 Атмосфера+2% SO_2	6 576	113	58
5 Атмосфера+5% SO_2+5%H_2O	15 242	358	43
6 Атмосфера+5% CO_2+5%H_2O	10 044	458	22
7 Чистый воздух+5% CO_2	7 688	118	65
8 Чистый воздух+5% H_2O	7 421	324	23

1 - Pure air; 2 - Ordinary atmosphere; 3 - Pure air 2% SO_2; 4 - Atmosphere 2% SO_2; 5 - Atmosphere 5% SO_2 5% H_2O; 6 - Atmosphere 5% CO_2 5% H_2O; 7 - Pure air 5% CO_2; 8 - Pure air 5% H_2O; 9 - Atmosphere; 10 - Weight gain, mg/dm²; 11 - low-carbon steel; 12 - steel Kh18N9; 13 - Ratio

Note: Diameter of specimen 1 cm, weight 20 g; surface preparation: grinding with No. 00 emery paper.

*Test period 24 hours, temperature 900°.

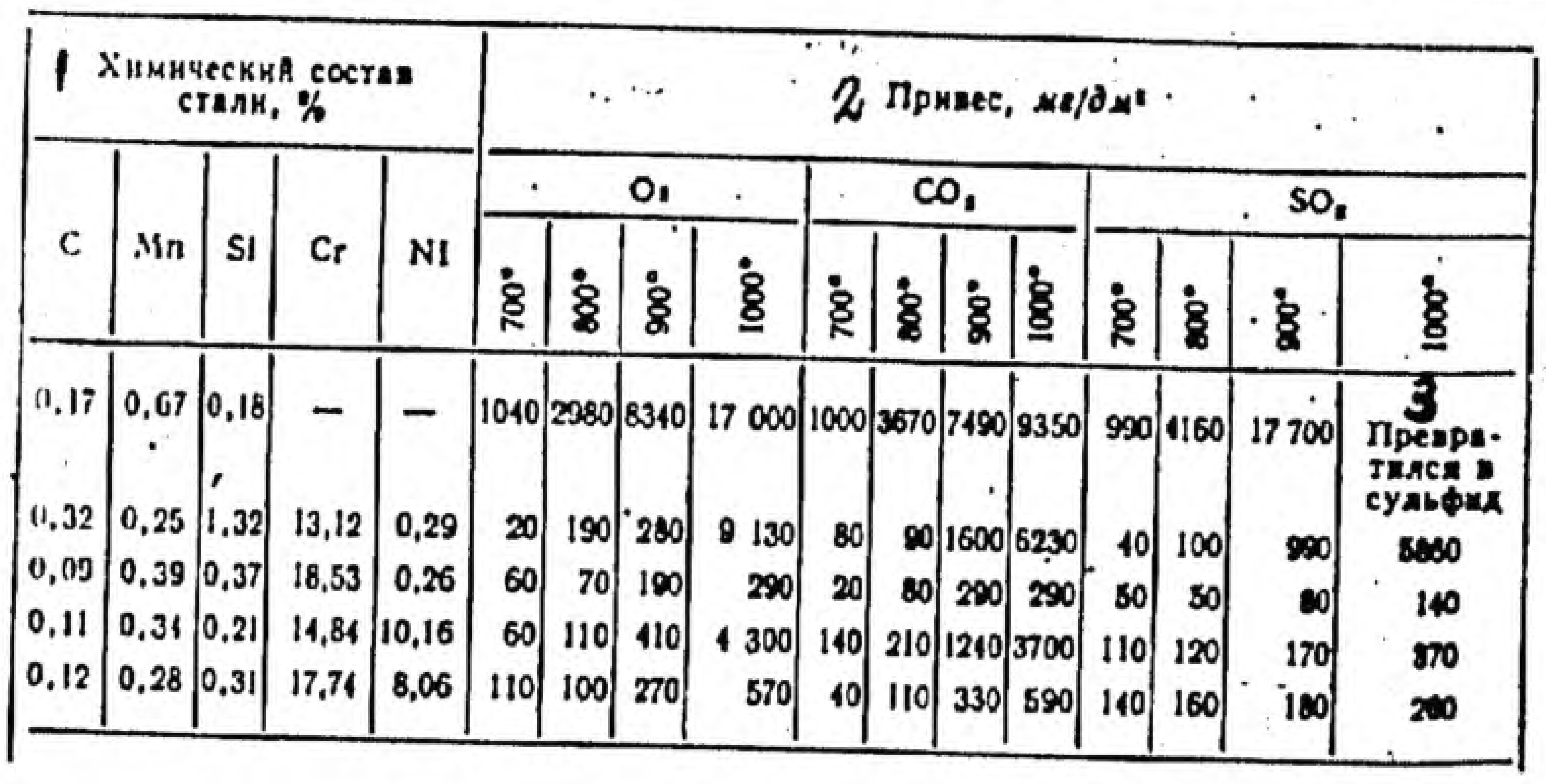
The influence of small additions of SO_2 to the furnace atmosphere on the resistivity of carbon, chromium, and chromium-nickel steel is shown in Fig. 38, from which it is to be seen that chromium--nickel steel of the Kh18N9 type is distinguished by high resistance to oxidation in a furnace atmosphere on addition of up to 0.21% sulfurous acid anhydride. Carbon and chromium steels undergo intensive oxidation under these conditions [8].

Steel of the Kh17 type with a higher silicon content is stable toward oxidation in an atmosphere of hot flue gases rich in sulfur [23].

Apparatus employed for petroleum refining is the most often subjected to the action of an atmosphere containing sulfur. Experience shows that with increase in the chromium content of steels, their corrosion resistance in petroleum distillation products containing sulfur compounds increases (Table 21).

Table 20

Oxidizability of Chromium And Chromium-Nickel Steels At High Temperatures In Various Gaseous Atmospheres [8]



1 Химический состав стали, %					2 Привес, мг/дм²											
					O_2				CO_2				SO_2			
C	Mn	Si	Cr	Ni	700°	800°	900°	1000°	700°	800°	900°	1000°	700°	800°	900°	1000°
0,17	0,67	0,18	—	—	1040	2980	8340	17 000	1000	3670	7490	9350	990	4160	17 700	3 Превратился в сульфид
0,32	0,25	1,32	13,12	0,29	20	190	280	9 130	80	90	1600	6230	40	100	990	5860
0,09	0,39	0,37	18,53	0,26	60	70	190	290	20	80	290	290	50	50	80	140
0,11	0,34	0,21	14,84	10,16	60	110	410	4 300	140	210	1240	3700	110	120	170	370
0,12	0,28	0,31	17,74	8,06	110	100	270	570	40	110	330	590	140	160	180	280

1 - Chemical composition of steel, %; 2 - Weight gain, mg/dm^2;
3 - Converted into sulfide.

Note: Weight of specimen 20 g; diameter of specimen in testing in O_2 2.5 cm, in CO_2 and SO_2 1 cm; surface preparation: grinding with No. 00 emery paper; rate of gas flow in O_2 and CO_2 110 l/h, in SO_2 55 l/h; test period 24 hours.

Table 21

Stability Of Chromium-Nickel Steels In Petroleum Distillation Products Containing Sulfur [8] At Temperatures of 345-400°

Gas cracking of petroleum		
Composition of steel or alloy, %		Corrosion rate, cm/year
Cr	Ni	
9	20	0.0033
14	80	0.00091
18	8	0.00005

In operation with fuel having a high sulfur content, use is generally made of steels with 15% Cr + 35% Ni, 25% Cr, and 20% Ni, often alloyed with silicon, since the latter improves their stability in atmospheres containing sulfur [8].

Table 22 and Figures 39 and 40 give data on the stability of chromium and chromium-nickel steels in hydrogen sulfide at elevated temperatures. The data show that hydrogen sulfide is a highly aggressive medium causing considerable scale formation with both unalloyed steels and iron and with chromium and chromium-nickel steels. At the same time, with increase in the chromium content of these steels, the stability of the latter in an atmosphere of hydrogen sulfide increases.

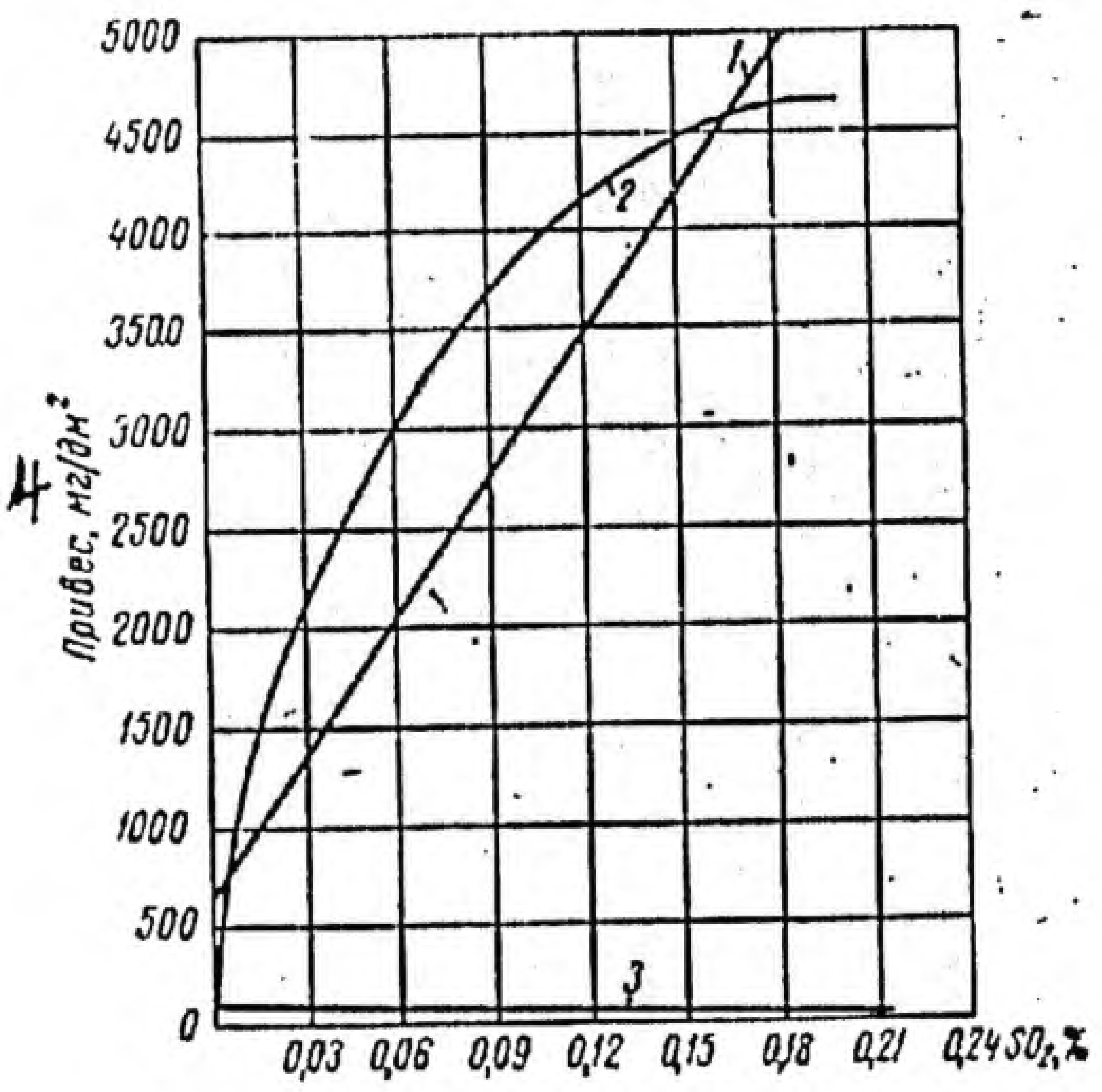


Fig. 38. Influence of small additions of SO_2 to furnace atmosphere on capacity of various steels to resist oxidation [8]. Test conditions: temperature, 1000°; test period, 1.5 hours; composition of furnace atmosphere: CO_2, 10%; H_2O, 10%; N_2, 80%:

1 - carbon steel containing 0.13% C;
2 - chromium steel containing 12% Cr;
3 - chromium-nickel steel of the Kh18N9 type;
4 - weight gain, mg/dm².

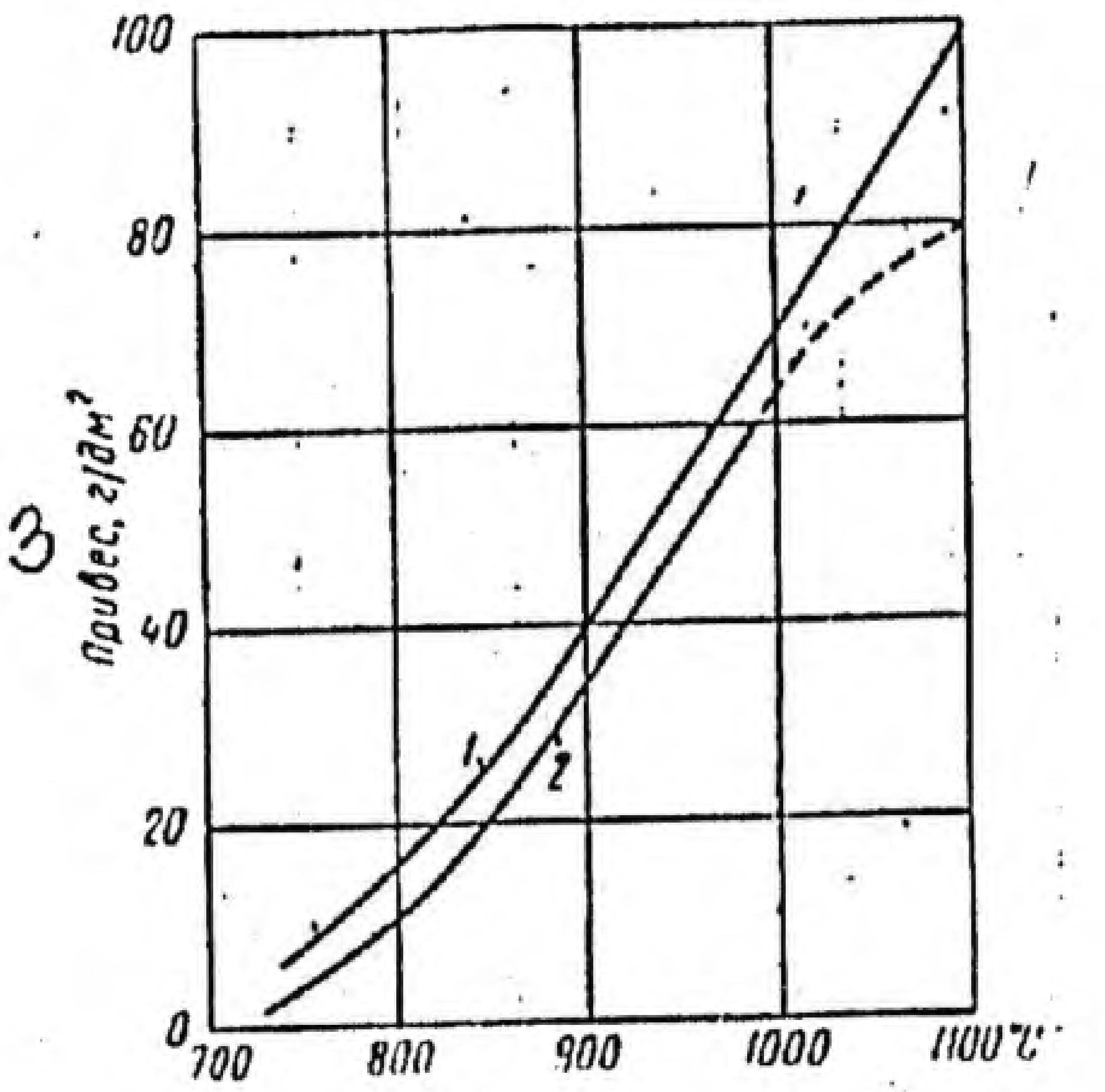


Fig. 39. Stability of chromium steels in hydrogen sulfide at high temperatures. Test period 25 hours [8]:

1 - steel containing 11% Cr;

2 - steel containing 28% Cr;

3 - weight gain, g/dm².

A high chromium content of steels also ensures better capacity to resist gas corrosion in sulfur vapor. Thus, for example, steels containing 28% Cr are stabler in sulfur vapor than are chromium-nickel steels, since in the presence of sulfur there is formed in the latter a low-melting eutectic in the form of nickelous sulfide, the melting point of which is around 650°. The protective action of the chromium consists in elevating the melting point of the sulfur compounds formed. When the steel contains chromium in the amount of 50%, the melting point of the sulfur compounds is elevated to 1175°.

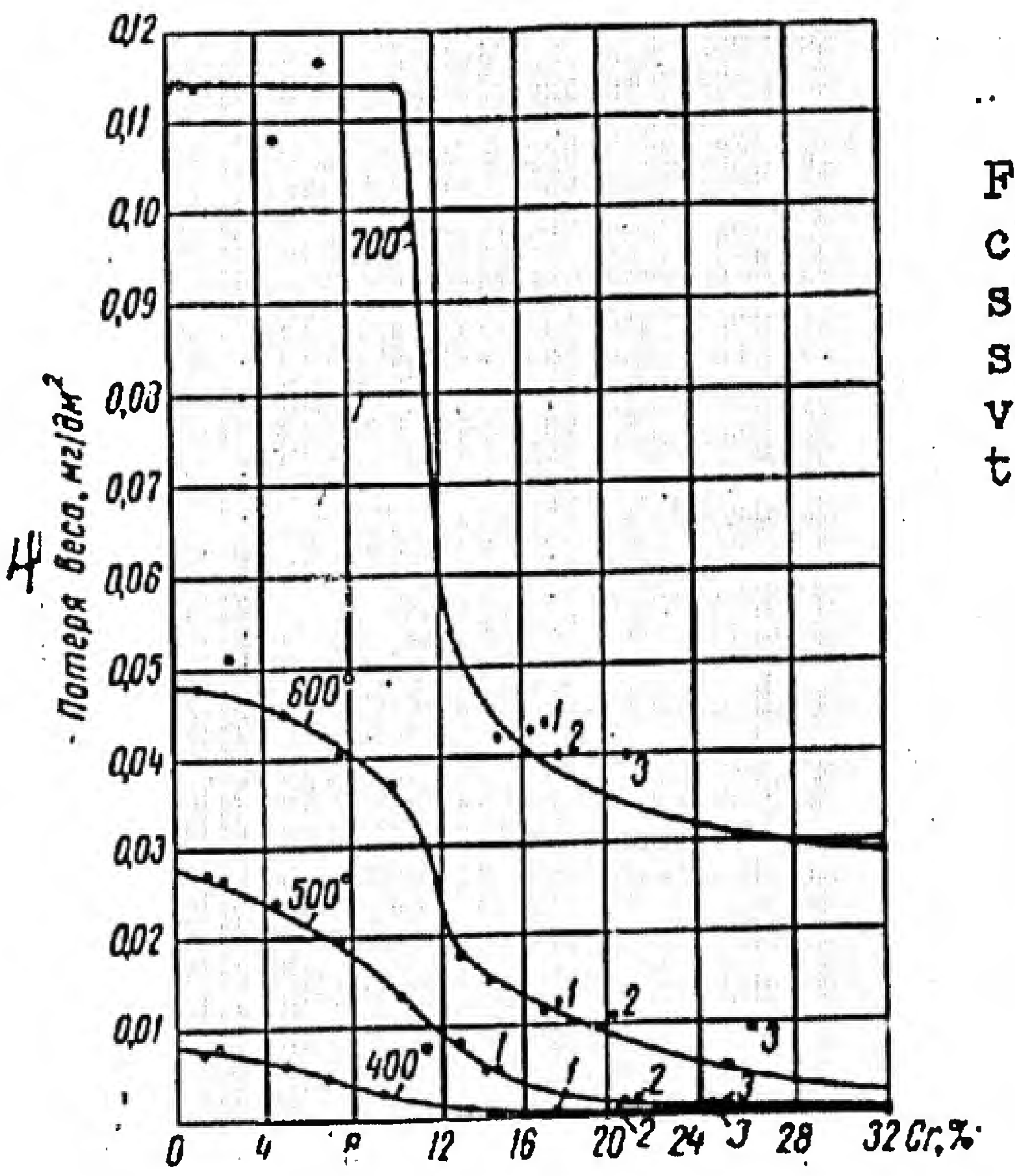


Fig. 40. Scale formation on chromium and chromium-nickel steels and alloys in hydrogen sulfide at various temperatures, versus the chromium content of the steels [8]:

- O - Chromium steels;
- ● - chromium-nickel steels and alloys;
- 1 - 9% Ni;
- 2 - 78% Ni;
- 3 - 20% Ni;
- 4 - weight loss, mg/dm².

Table 22

Stability Of Chromium And Chromium-Nickel Steels In Hydrogen Sulfide At Elevated Temperatures [8]

1 Состав стали, %		2 Привес, мг/дм²					
Cr	Ni	480°; 28,5 ч 3	650°; 24 ч 3	700°; 1 ч 3	800°; 1 ч 3	900°; 1 ч 3	1000°; 1 ч 3
4 Железо	—	—	—	1320	9600	17 400	5 Превратился в сульфид
6 Малоуглеродистая сталь		3400	—	—	—	—	—
8	—	3000	—	—	—	—	—
13	—	—	15 100	—	—	—	—
14	—	1900	—	—	—	—	—
17	26	480	—	—	—	—	—
19	—	560	—	—	—	—	—
20	—	—	11 700	—	—	—	—
20	8	—	9 400	—	—	—	—
24	25	—	—	750	5500	14 100	21 800
25	—	560	—	1010	5500	13 800	23 000
26	22 и 7 3,2 Si	500	—	—	—	—	—

1 - Composition of steel, %; 2 - weight gain, mg/dm²; 3 - hours; 4 - Iron; 5 - Converted into sulfide; 6 - Low-carbon steel; 7 - And.

The addition to high-chromium steels of the Kh28 type of aluminum in the amount of 1.5% lowers their stability in sulfur vapor (Table 23).

Table 23

Stability Of High-Chromium Steel In Sulfur Vapor [8]

1 Сталь с 28% Cr			2 Сталь с 25% Cr и 1,5% Al		
3 Температура испытаний °C	4 Скорость коррозии		3 Температура испытаний °C	4 Скорость коррозии	
	6 см/год	6 мг/дм²·сутки		5 см/год	6 мг/дм²·сутки
295	0,0229	48,7	295	0,046	97,5
360	0,0229	48,7	375	0,046	97,5
455	0,071	149,5	495	0,137	292,5
575	0,117	247	620	0,183	390
700	0,254	553	745	0,61	1300
820	0,79	1690	845	1,55	3355
880	1,47	3120	915	2,18	4680
930	1,83	3900	955	2,64	5655
950	2,29	4875	980	2,64	5655
955	2,54	5395	990	2,64	5655

1 - Steel containing 28% Cr; 2 - Steel containing 25% Cr and 1.5% Al; 3 - Test temperature, °C; 4 - Corrosion rate; 5 - cm/year; 6 - mg/dm^2 • 24 hours.

Fig. 41 illustrates the behavior of various oxidation-resistant steels in a carburizing atmosphere. Chromium steels containing up to 18% chromium are characterized by low stability in this atmosphere. Thus, steels 2Kh13 and Kh6SYu are heavily carburized (up to 3.0 - 3.5% C); they warp, sharp edges fuse, and the surface is covered with pits. These same steels are considerably saturated with the gases oxygen, nitrogen, and hydrogen (Figures 42 - 44).

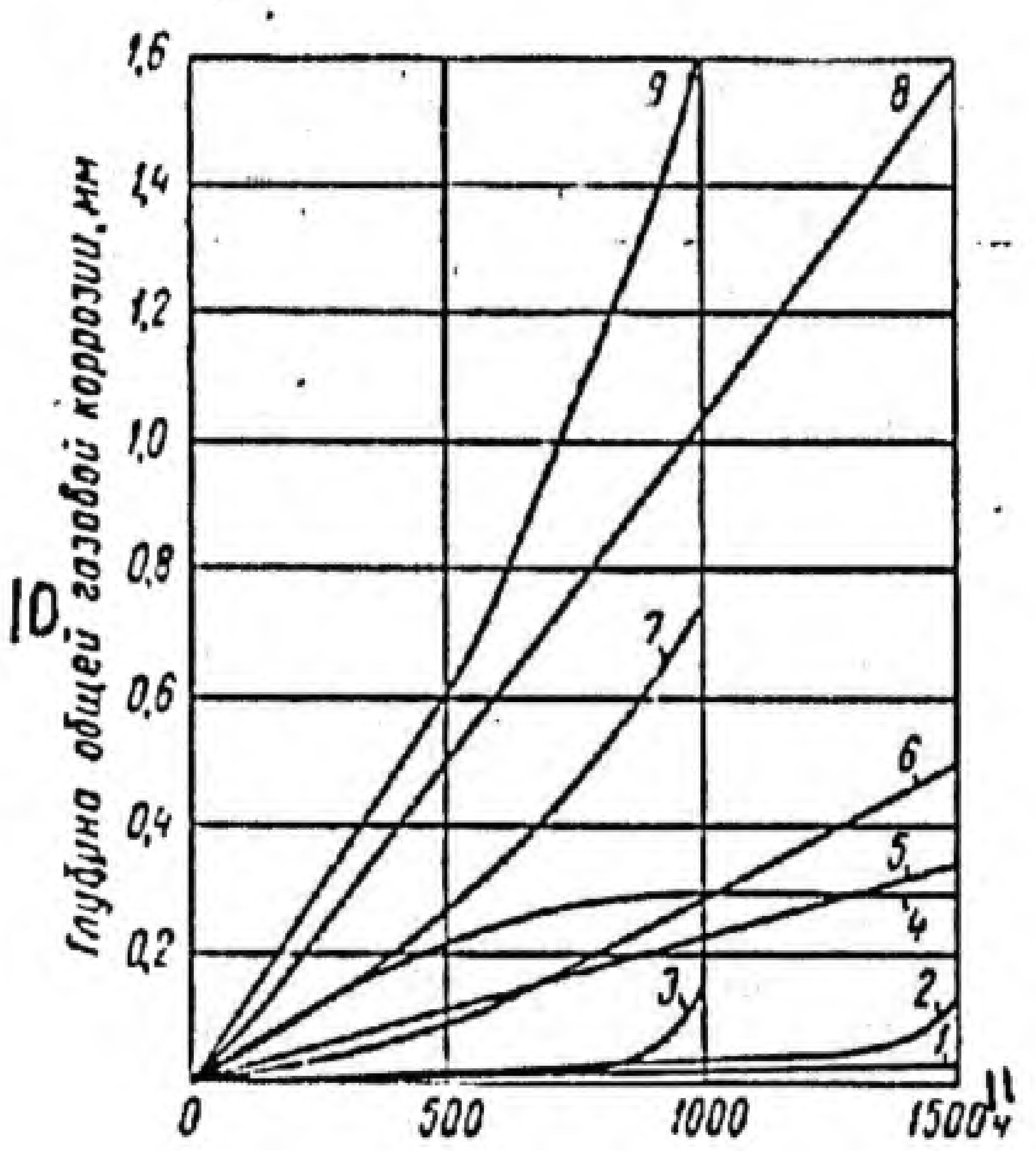


Fig. 41. Kinetics of oxidation of certain oxidation-resistant steels in a carburizing atmosphere at 1050° [33]: composition of atmosphere: CO_2 0.1-0.2%; CO 30-35%; H_2 55-60%; CH_4 0.1-0.5%; N_2 remainder.

1 - Kh23N18;
2 - Kh25N16G7AR;
3 - Kh25N25TR;
4 - Kh18SYu;
5 - Kh17;
6 - Kh25T;
7 - 1Kh13;
8 - Kh12SYu;
9 - Kh6SYu;
10 - Depth of general gas corrosion, mm;
11 - Hours.

2. THERMOSTABLE STEELS

Thermostable steels are employed in various branches of industry: boiler and turbine construction, mechanical engineering, the chemical industry, etc.. They are predominantly low and medium-alloy steels of the pearlite class. They are thermostable in the 500-600° temperature range and are utilized chiefly for the manufacture of the pipes of power plants, cylinders, steam and nozzle boxes, shaped castings for fittings and high-pressure pipelines, and for fastenings operating at elevated temperatures and subjected to the action of aggressive media (steam, humid air, an atmosphere containing sulfur, etc).

Tables 24-27 give the chemical composition and the basic physical, mechanical, and technological properties of steels employed in boiler, turbine, and engine construction.

The forms of semiproducts and the GOSTs governing the delivered output from these steels are shown in Table 28.

These tables show that from the standpoint of rate of oxidation in air at 550-585°, the majority of the steels enumerated, belong in the group of "stable" steels and correspond to points 4 and 5 as established by GOST 5272-50. At 600-610° the stability of these steels toward oxidation decreases, being given the rating of 6 in the group of steels of lower stability. An exception is steel 25Kh2M1F, the corrosion rate of which in air is 0.19 mm/year even at 550°.

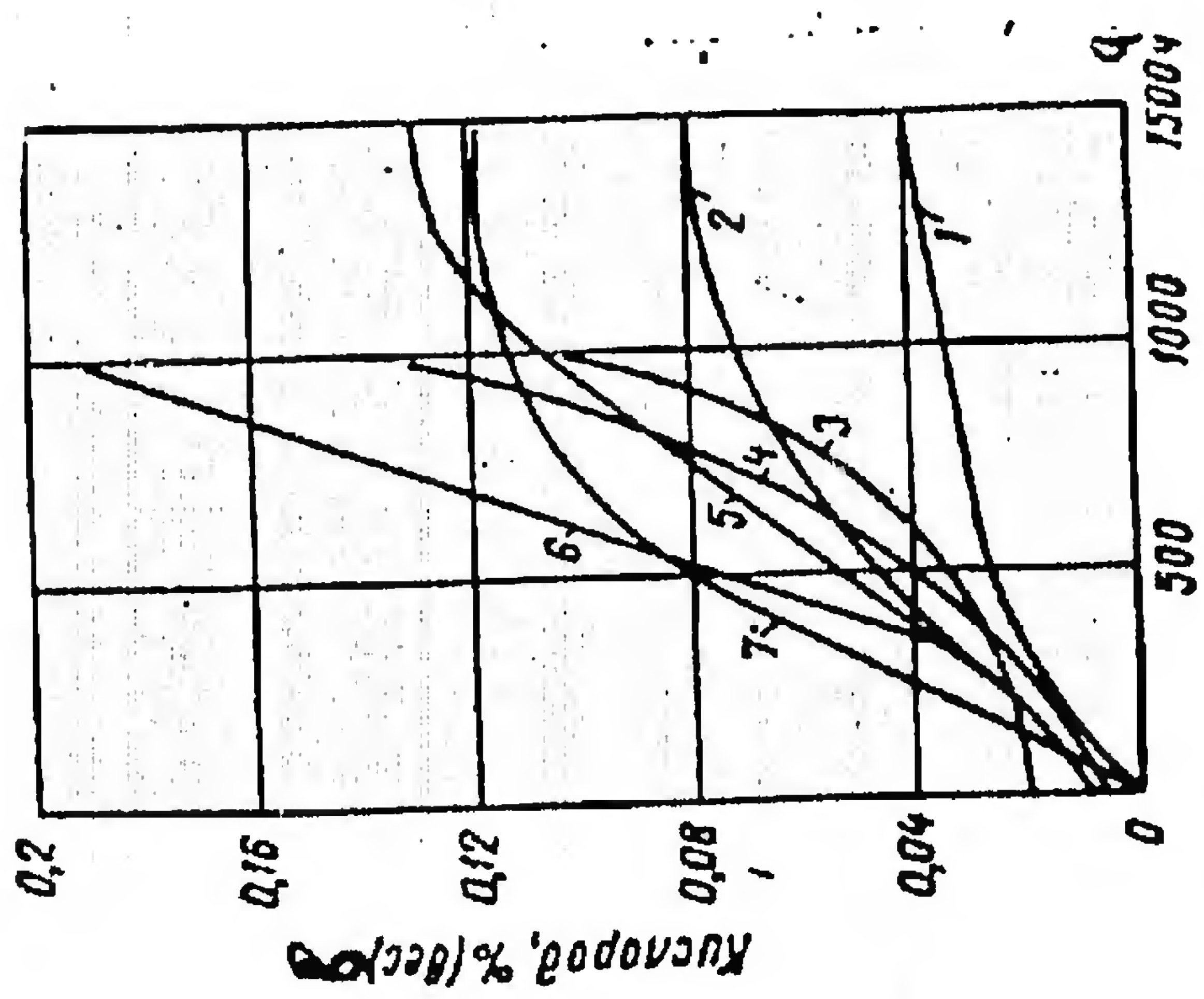
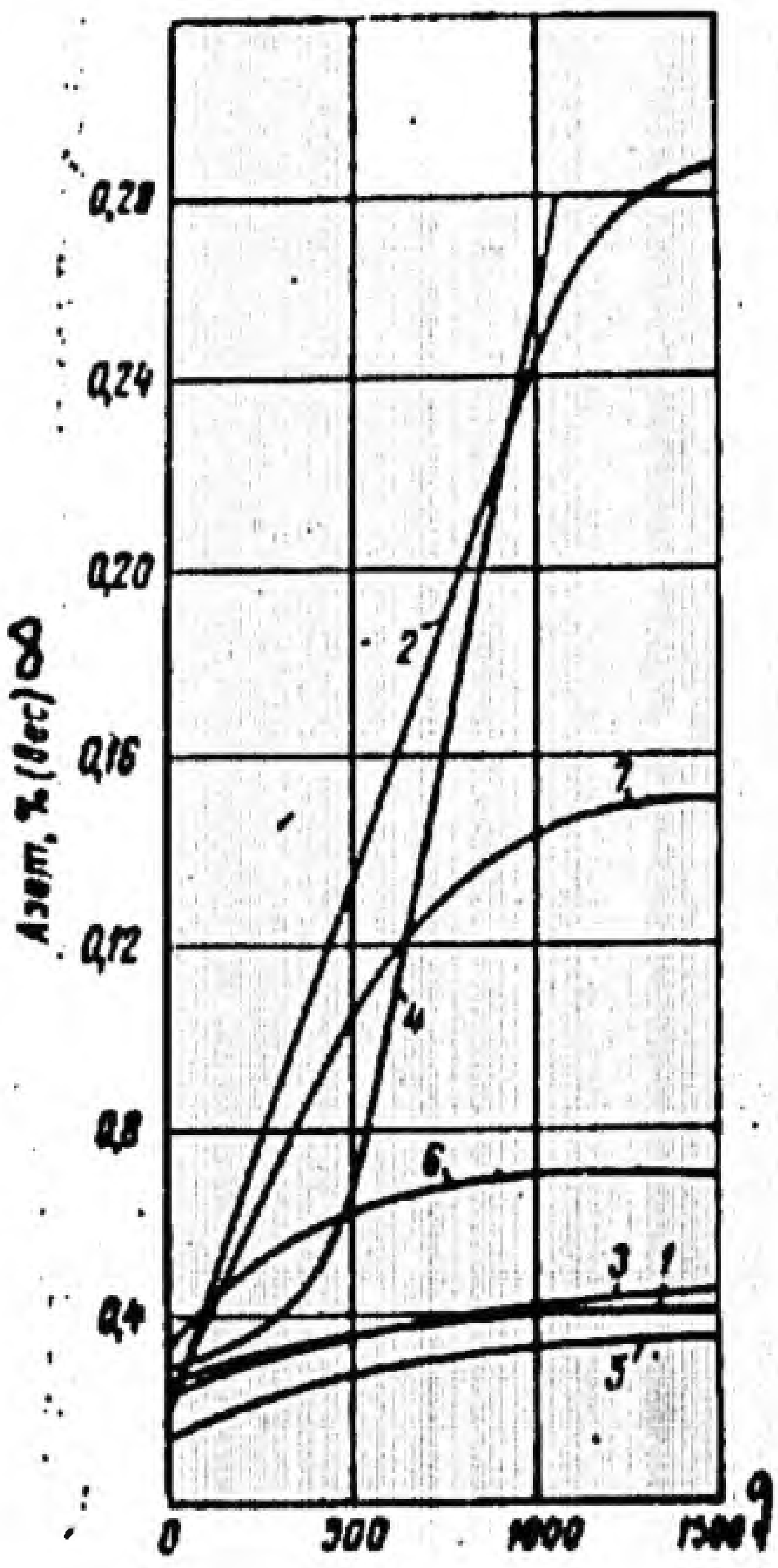


Fig. 42. Saturation of certain oxidation-resistant steels with oxygen in a carburizing atmosphere at 1050° [33]:

1 - Kh25;
2 - Kh12SYu;
3 - 1Kh13;
4 - Kh6SYu;
5 - Kh25T;
6 - Kh17;
7 - Kh18SYu;
8 - Oxygen, % (weight);
9 - hours.

Fig. 43. Saturation of certain oxidation-resistant steels with nitrogen in a carburizing atmosphere at 1050° [33]:

1 - Kh25;
2 - Kh12SYu;
3 - 1Kh13;
4 - Kh6SYu;
5 - Kh25T;
6 - Kh17;
7 - Kh18SYu;
8 - Nitrogen, % (weight)
9 - Hours.



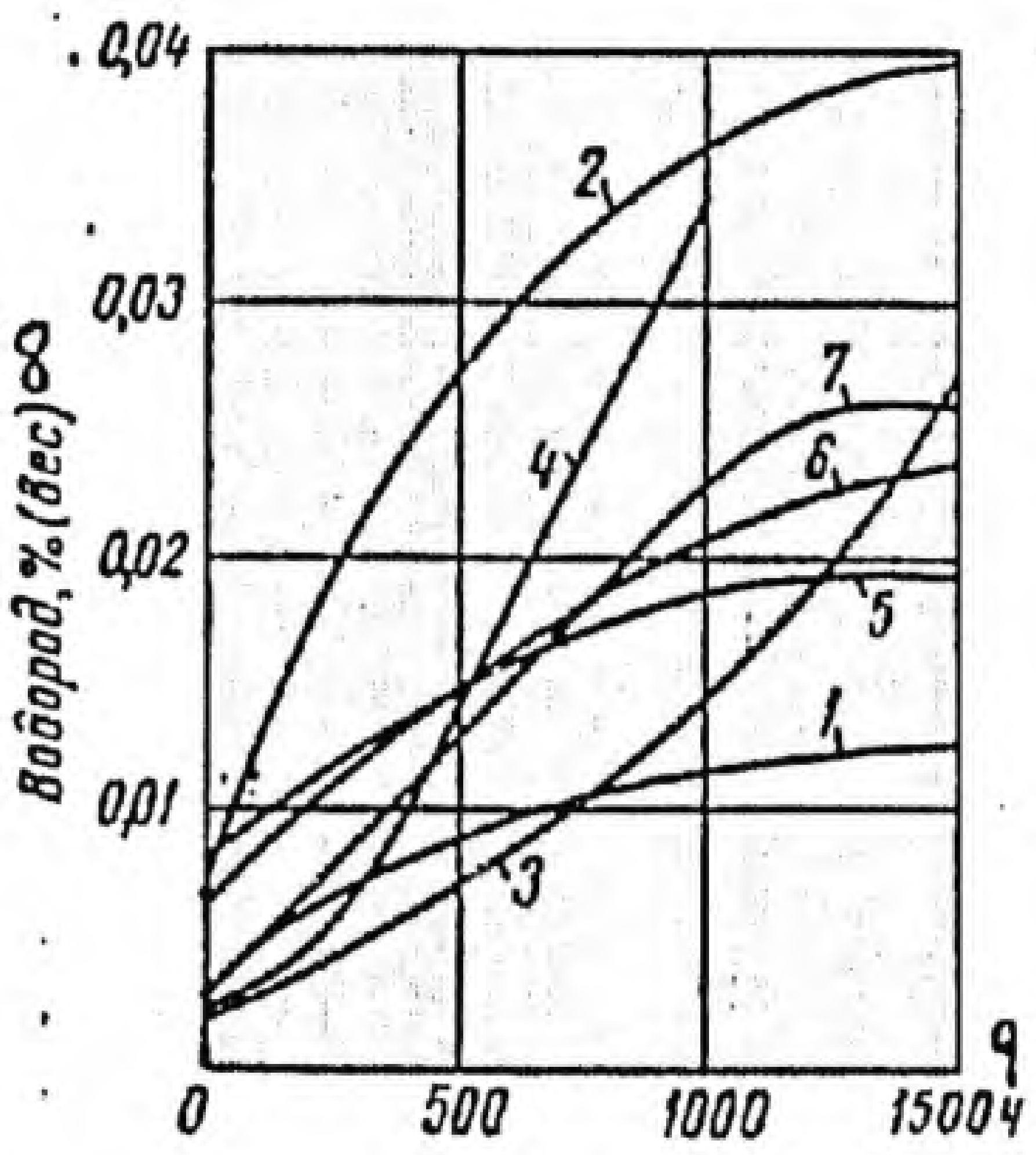


Fig. 44. Saturation of certain oxidation-resistant steels with hydrogen in a carburizing atmosphere at 1050° [33]:
1 - Kh25;
2 - Kh12SYu;
3 - 1Kh13;
4 - Kh6SYu;
5 - Kh25T;
6 --Kh17;
7 - Kh18SYu;
8 - Hydrogen, % (weight);
9 - Hours.

Table 24

Certain Properties And Purpose Of Thermostable Steels Employed In Boiler, Turbine, And Engine Construction

Brand of Steel	Specific gravity, g/cm^3	Linear expansion coefficient at 20 - 100 X 10^6	Thermal conductivity cal/cm • sec • °C
12 MKhF (12KhMF)	7.8	10.8	0.109 at 20°
12Kh1MF (12KhMF, E1575	7.8	10.8	0.085 at 20°
15Kh1M1F	7.8	11.2	0.099 at 100°
25Kh1M1F (R2)	7.82	10.9	0.085 at 100°
25Kh2MFA (25Kh1MF, E110)	7.84	11.3	0.100 at 100°
25Kh2M1F (25Kh2M1F1A, E1723)	7.8	12.5	0.065 at 100°
20Kh3MVF (E1415, E1579)	7.8	12.3	0.092 at 20° 0.085 at 100°
15Kh1M1FL	-	12.4	0.077 at 100°
Kh11L-A Kh11L-B	7.8	10.3	0.06 at 100°

Table 24 (Cont'd)

Brand of Steel	Corrosion rate, mm/year	Basic Purpose
12MKhF (12KhMF)	0.07 at 550°	Pipes for steam superheaters, pipelines, and collectors of high-pressure plants (operating temperature up to 550°), forged pieces for parts of steam lines. Mechanical properties stable up to 500°
12Kh1MF(12KhMF, E1575)	0.07 at 585° 0.12 at 600°	Same, operating temperature 570-580°
15Kh1M1F	0.09 at 570° 0.17 at 610°	Steam lines and steam superheaters of high-pressure boiler plants (operating temperature 585°), diaphragms of steam turbines, etc.
25Kh1M1F (R2)	Operating temperature 500 - 550°	Seamless forged rotors and disks of turbines (operating temperature 535-540°); fastenings (operating temperature 500-525°). The properties of the steel are characterized by stability up to 500° under protracted heating (up to 10,000 hours) and by high-temperature indices up to 500 - 550°.
25Kh2MFA (25Kh1MF, E110)	Operating temperature 500-570°	Fastenings (bolts, studs) of turbines (operating temperature 500-510°). The steel is heat-resistant up to 500° and ductile under protracted rupture stress
25Kh2M1F (25Kh2M1F1a, E1723)	0.19 at 550°	Fastenings and springs of labyrinth glands of steam turbines (operating temperature up to 550°
20Kh3MVF (E1415, E1579)	Operating temperature 540°	Fastenings (operating temperature 540° up to 100,000 hours; up to 580° for shorter periods), seamless forged rotors, turbine disks and compressor disks (operating temperature 480-540°). The most heat-resistant of all the steels of the pearlite class.

Table 24 (Cont'd)

Brand of Steel	Corrosion rate, mm/year	Basic Purpose
15Kh1M1FL	0.09 at 570° 0.17 at 610°	Cast turbine parts (cylinders, steam and nozzle boxes; operating temperature 565-580°), section castings for fittings and high-pressure pipelines (operating temperature 570°
Kh11L-A Kh11L-B	0.08 at 580° (in an atmosphere of steam); 0.03 at 580° in an atmosphere of moist air (15% H_2O); same, 0.11 at 600°	Cast parts of turbines (cylinders, nozzles, diaphragms) and fittings (operating temperature 580-600°)

Table 25

Chemical Composition Of Thermostable Steels Employed In Boiler, Turbine, And Engine Construction

1 Марка стали	2 ГОСТ или ТУ	3 Содержание элементов, %									4 Другие элементы
		C	Si	Mn	Cr	Mo	V	W	S	P	
5 12МХФ (12ХМФ)	6 ЧМТУ 579—54 6 ЧМТУ 2580—54	0,08—0,15	0,15—0,35	0,4—0,7	0,4—0,6	0,25—0,35	0,15—0,30	—	<0,04	<0,04	—
7 12Х1МФ (12ХМФ, ЭИ575)	6 ЧМТУ 2579—54 6 ЧМТУ 2580—54	0,08—0,15	0,17—0,37	0,4—0,7	0,9—1,2	0,25—0,35	0,15—0,30	—	<0,025	<0,030	—
8 15Х1М1Ф	9 Дополнение к ЧМТУ 2579—54 6 ЧМТУ 2580—54	0,10—0,17	0,15—0,35	0,4—0,7	1,1—1,4	0,9—1,1	0,20—0,35	—	<0,03	<0,03	—
10 25Х1М1Ф (Р2)	11 Заводские ТУ	0,22—0,29	0,3—0,5	<0,6	1,5—1,8	0,6—0,8	0,2—0,3	—	<0,025	<0,03	—
12 25Х2МФА (25Х1МФ, ЭИ10)	13 ГОСТ 4543—61	0,22—0,29	0,17—0,37	0,4—0,7	1,5—1,8	0,2—0,3	0,15—0,30	—	<0,03	<0,035	—
14 25Х2М1Ф (ЭИ723, 25Х2М1Ф1А)	6 ЧМТУ 5664—56	0,22—0,30	0,17—0,37	0,5—0,8	2,1—2,5	0,9—1,1	0,3—0,5	—	<0,03	<0,03	—
15 20Х3МВФ (ЭИ415, ЭИ579)	16 МПТУ 2362-49	0,16—0,24	<0,4	0,25—0,60	2,4—3,3	0,35—0,55	0,6—0,85	0,3—0,5	<0,03	<0,035	—
17 15Х1М1ФЛ	18 Нормаль МВН 632—58	0,14—0,20	0,15—0,37	0,4—0,7	1,2—1,7	1,0—1,2	0,2—0.4	—	<0,03	<0,03	—
19 Х11Л-А (15Х11МФБЛ)	11 Заводские ТУ	0,12—0,19	<0,5	0,5—1,0	10—10,5	0,6—0,8	0,25—0,30	—	<0,03	<0,03	0,6+1,0 Ni 0,15+0,25 Nb
20 Х11Л-В (15Х11МВФЛ)	11 Заводские ТУ	0,12—0,19	<0,5	0,5—1,0	10,5—12	0,6—0,8	0,25—0,30	0,8—1,1	<0,03	<0,03	0,6+1,0 Ni

1 - Brand of steel; 2 - GOST or specification; 3 - Content of elements, %; 4 - Other elements; 5- 12MKhF (12KhMF); 6 - ChMTU; 7 - 12Kh1MF (12KhMF, E1575); 8 - 15Kh1M1F; 9 - Supplement to ChMTU; 10 - 25Kh1M1F (R2); 11 - Plant specifications; 12 - 25Kh2MFA (25Kh1MF, E110); 13 - GOST; 14 - 25Kh2M1F (E1723, 25Kh2M1F1A); 15 - 20Kh3MVF (E1415, E1579); 16 - MPTU; 17 - 15Kh1M1FL; 18 - Standard specifications MVN 632-58; 19 - Kh11L-A (15Kh11MFBL); 20 - Kh11L-B (15Kh11MVFL).

Table 26

Mechanical Properties Of Thermostable Steels Employed In Boiler, Turbine, And Engine Construction

1 Марка стали	2 Режим термической обработки	Предел текучести $\sigma_т$, кГ/мм² 3	Предел прочности $\sigma_в$, кГ/мм² 4	Относительное удлинение δ_5, % 5	Поперечное сужение ψ, % 6	Ударная вязкость $a_н$, кГ·м/см² 7	8 Примечание
9 12МХФ (12ХМФ)	10 Нормализация 980—1000°, отпуск при 740—760°	31	50	23	71	13	11 Продольные образцы
12 12Х1МФ (12ХМФ, ЭИ575)	13 Нормализация 960—980°, отпуск при 740—760°	30—38	51—54	29—31	71—73	16—20	14 Тангенциальные образцы
15 15Х1М1Ф	16 Нормализация 1000—1050°, отпуск 700°	38	60	23	73	21	17 Тангенциальные образцы
18 25Х1М1Ф (Р2)	19 Двойная нормализация (970—990° и 930—950°), отпуск при 680—700°	53—59	69—74	15—19	41—64	2—10	20 Тангенциальные образцы
21 25Х2МФА (25Х1МФ, ЭИ10)	22 Закалка с 930—950° в масле, отпуск при 620—660°	81—102	90—107	16—19	60—64	—	23 E=21 700 кГ/мм²
25Х2М1Ф 24 (25Х2М1Ф1А, ЭИ723)	25 Нормализация 1050°, отпуск при 650°	≥75	≥90	≥12	≥50	≥5*	26 E=22 100 кГ/мм²
27 15Х1М1ФЛ	28 Нормализация 980—1000°, отпуск при 710—740°	35—50	55—60	22	69	4—18	29 E=22 000 кГ/мм²
30 Х11Л-Б (15Х11МВФЛ)	31 Отжиг 950°, двойная нормализация (1100 и 1050°) с ускоренным охлаждением, отпуск при 680° 10—20 ч или при 700° 8—10 ч	≥50	≥60	≥15	≥50	≥5	32 E=21 000 кГ/мм²
33 20Х3МВФ (ЭИ415, ЭИ579)	34 Закалка с 1030—1080° в масле, отпуск 660—700°	75—83	89—93	13	49	4	35 Тангенциальные образцы E=21 000 кГ/мм²

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36 * Приближенно.

Explanation of Table 26:

1 - Brand of steel; 2 - Heat treatment conditions; 3 - Yield point, σ_T, kG/mm^2; 4 - Ultimate strength, σ_V, kG/mm^2; 5 - Elongation per unit length, δ_5, %; 6 - Transverse contraction, ψ, %; 7 - Impact toughness, a_n, kG • m/cm^2; 8 - Remarks; 9 - 12MKhF (12KhMF); 10 - Normalizing 980-1000°, tempering at 740-760°; 11 - Linear specimens; 12 - 12Kh1Mf (12KhMF, E1575); 13 - Normalizing 960-980°, tempering at 740-760°; 14 - Tangential specimens; 15 - 15Kh1M1F; 16 - Normalizing 1000-1050°, tempering at 700°; 17 - Tangential specimens; 18 - 25Kh1M1F (R2); 19 - Double normalizing (970-990° and 930-950°), tempering at 680-700°; 20 - Tangential specimens; 21 - 25Kh2MFA (25Kh1MF, E110); 22 - Quenching from 930-950° in oil, tempering at 620-660°; 23 - E = 21,700 kG/mm^2; 24 -25Kh2M1F (25Kh2M1F1A, E1723); 25 --Normalizing 1050°, tempering at 650°; 26 - E = 22,100 kG/mm^2; 27 - 15Kh1M1FL; 28 - Normalizing 980-1000°, tempering at 710-740°; 29 - E = 22,000 kG/mm^2; 30 - Kh11L-B (15Kh11MVFL); 31 - Annealing 950°, double normalizing (1100 and 1050°) with accelerated cooling, tempering at 680° for 10-20 hours or at 700° for 8-10 hours; 32 - E = 21,000 kG/mm^2; 33 - 20Kh3 MVF (E1415, E1579); 34 - Quenching from 1030-1080° in oil, tempering at 660-700°; 35 - Tangential specimens, E = 21,000 kG/mm^2; 36 - Approximately.

Table 27

Technological Properties Of Thermostable Steels Employed In Boiler, Turbine, And Engine Construction 45, 51

Brand of Steel	Technological Properties
12MKhF (12KhMF)	Lends itself well to machining and welding. TsL-20 electrodes used for welding; articles preheated to 300° before welding.
12Kh1MF (12KhMF, E1575)	Lends itself well to machining and welding. TsL-20 electrodes used for welding for operating temperatures up to 565°, and TsL-27 for higher temperatures. Articles preheated to 300° before welding.
15Kh1M1F	TsL-27 electrodes used in welding. Weld characterized by high mechanical properties in the 20-600° temperature range.
25Kh1M1F (R2)	May be employed for large forgings.
25Kh2MFA (E110, 25Kh1MF)	Employed in the normalizing state with subsequent tempering or after quenching and tempering. First-named form of heat treatment ensures high relaxation stability, the second lowers the sensitivity to notching under protracted rupture stress.

Table 27 (Cont'd)

Brand of Steel	Technological Properties
25Kh2M1F (E1723, 25Kh2M1F1A)	Characterized by satisfactory deformability in hot state; can be rolled and forged without particular difficulty. Has its optimum strength characteristics at high temperatures in the normalizing state with subsequent tempering.
20Kh3MVF (E1415, E1579)	Has been adopted in the production of large turbine forgings (seamless forged rotors and disks). Has its optimum properties in the normalizing state at 1050-1150° with subsequent quenching and tempering. Has high hardenability. Weldability satisfactory if preheated to 500°; TsL-20 electrodes with special coating.
15Kh1M1FL	Mechanical properties of castings depend on wall thickness (weight of castings). In large castings (weighing 5 tons) fluctuations in values of σ_T may reach 100% and in δ_y up to 50%. Castings of this steel welded with TsL-27 electrodes; castings preheated at 270-300°; tempering at 720° after welding.
Kh11L-A and Kh11L-B	Steels welded with KTI-10 electrodes, the composition of which is near that of the basic metal; preheating to 300°-350°; tempering at 680-700° after welding.

Certain steels, such as 25Kh1M1F, 25Kh2MFA, and 20Kh3MVF, are characterized by increased high-temperature strength in the 500-550° temperature range.

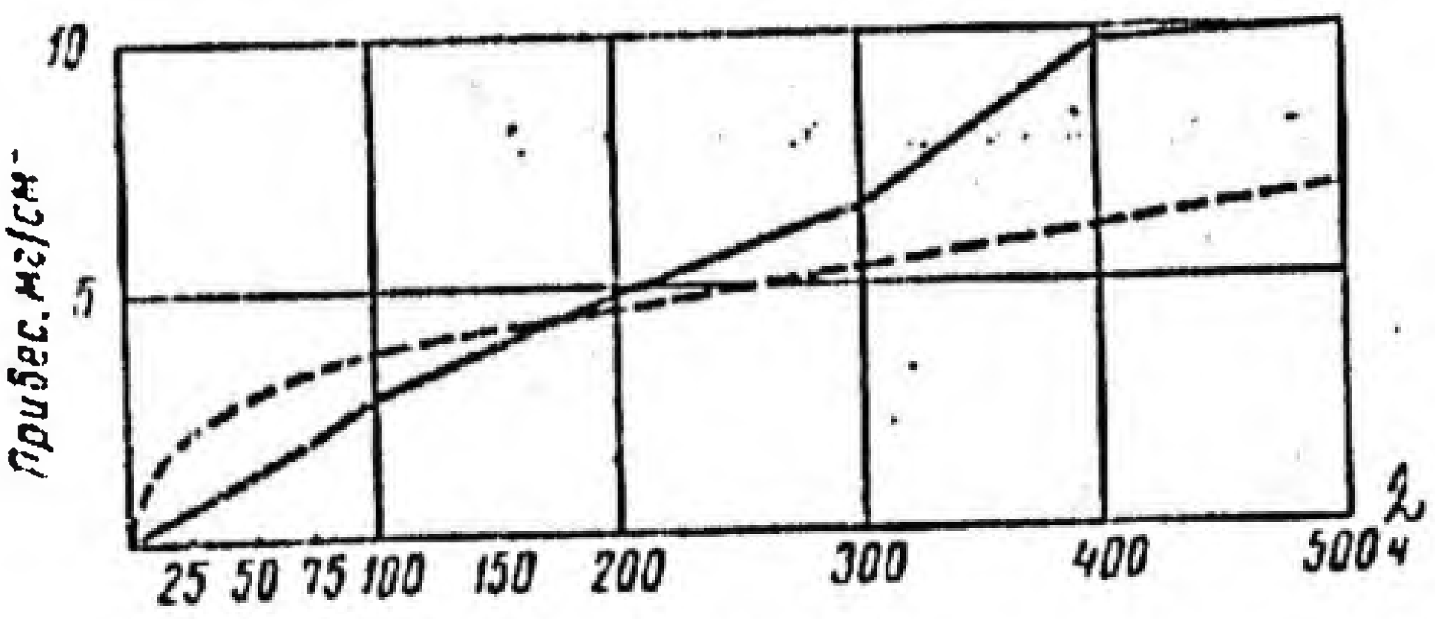

Fig. 45. Kinetics of oxidation of steel 15Kh1M1F in air and in superheated steam at 600° [27]: ······· - in superheated steam; -------- - in air; 1 - weight gain, mg/cm²; 2 - hours.

As regards the kinetics of oxidation of the group of thermostable steels, it can be represented by steel of brand 15Kh1M1F, which has received the greatest amount of study and the widest use, and also by steel 12MKhF.

Fig. 45 shows curves of oxidation of steel 15Kh1M1F in air and in superheated steam at a temperature of 600°. The pattern of oxidation of steel 15Kh1M1F in 500 hours in air may be expressed by the equation $g^{1.16} = 0.032\tau$, and in superheated steam $g^{2.7} = 0.341\tau$.

Shown in Fig. 46 is oxidation of steel 15Kh1M1F in air plotted against temperature, 600-700°. It is to be seen from the illustration that intensive oxidation of the steel begins on heating above 650°.

Table 28

Forms of Semiproducts Of Thermostable Steels Employed in Boiler, Turbine, and Engine Construction And Standards Governing Delivered Output

Brand of Steel	Seamless pipes	Forgings	Other forms of semi-products
12MKhF	ChMTU 2570--54 ChMTU 2580--54 ChMTU 3212--52	Plant standards	--
12Kh1MF (12KhMF, E1575)	ChMTU 2579-54 ChMTU 2580-54 ChMTU 3217-52	Departmental and plant specifications	--
15Kh1M1F	Supplement to ChMTU 2579-54 & ChMTU 2580-54	Plant specifications	--
25Kh1M1F1 (R2)	---	Plant specifications	--
25Kh2MFA (25Kh1MF, E110)	---	GOST 8479--57, plant specifications	Hot rolled merchants shapes (GOST 4543-61), hot rolled bars (GOST 4543-61, cold rolled rods (GOST 1051-59, ChMTU 3328-52, ChMTU 5260--55, silver steel rods (GOST 2588-44, ChMTU 5260-55)
25Kh2M1F (E1723, 25Kh2M1F1A)	---	---	Hot rolled and forged rods (ChMTU 5664-56)
20Kh3MVF (E1415, E1579)	---	ChMTU 5612-56, plant specifications	Hot rolled merchant shapes (MPTU 2362-49), hot rolled bars (MPTU 2362-49)
15Kh1M1FL	---	---	Shaped castings (departmental and plant specifications)
Kh11L-A and Kh11L-B	---	---	Shaped castings (plant specifications

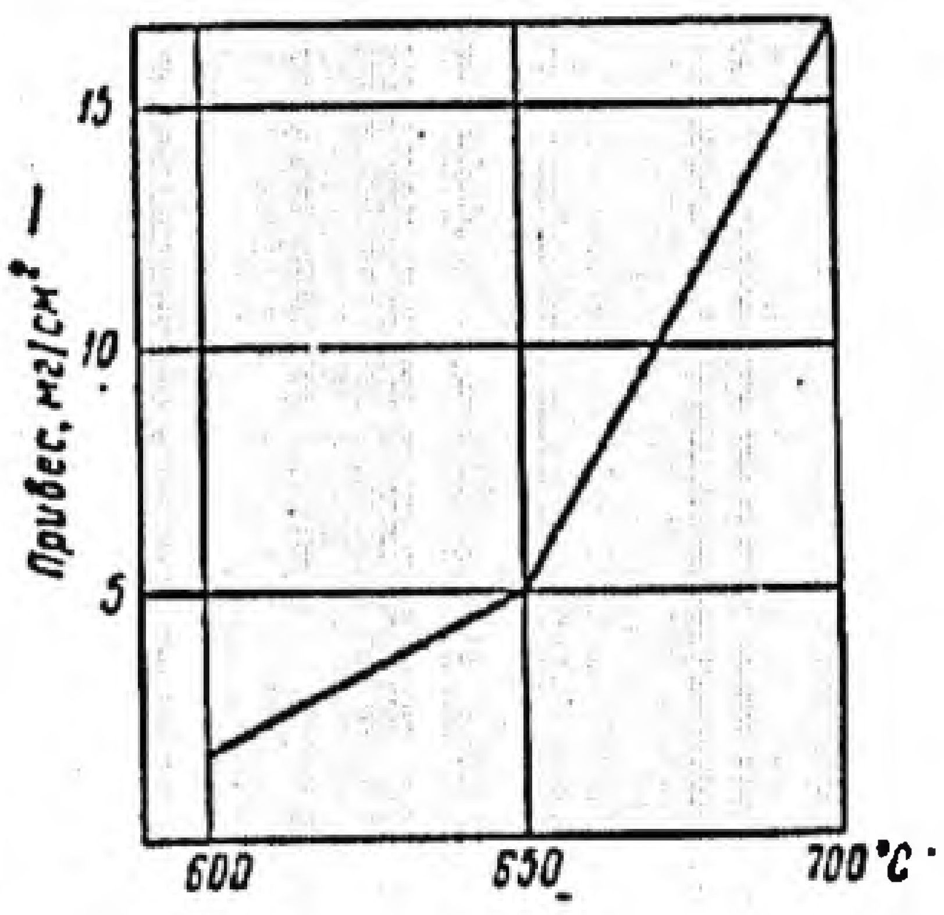

Fig. 46. Oxidation of steel 15Kh1M1F in air versus temperature in the 600-700° range [27]: 1 - weight gain, mg/cm².

The curve of oxidation of steel 12MKhF in superheated steam[26]500° is given in Fig. 47.

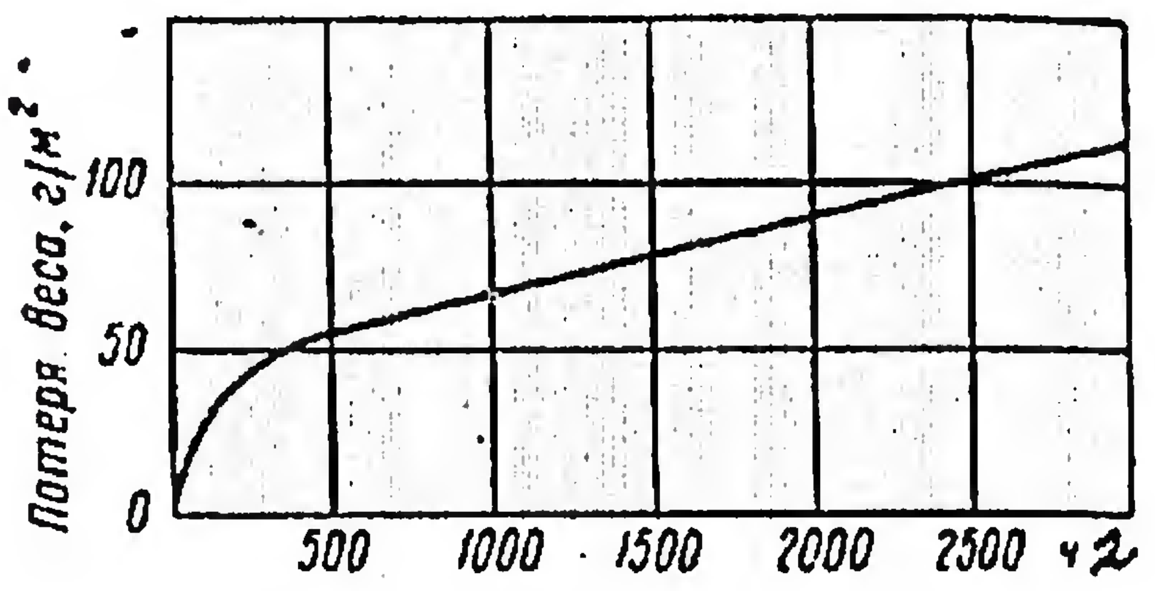

Fig. 47. Kinetics of oxidation of steel 12KhMF in superheated steam at a temperature of 500° [53].

3. SPECIAL-PURPOSE OXIDATION-RESISTANT METALS AND ALLOYS

High-alloy oxidation-resistant alloys* are employed for turbine parts manufactured from sheets, the parts of gas pipeline systems, and miscellaneous apparatus. These alloys have been especially widely used for the heating elements of electric furnaces.

The alloys utilized for heating elements usually represent a solid solution as regards phase state, since, as is well known, on the formation of solid solutions, the properties of alloys are considerably higher than with original metals A and B (Fig. 48). This pertains primarily to the electrical resistance.

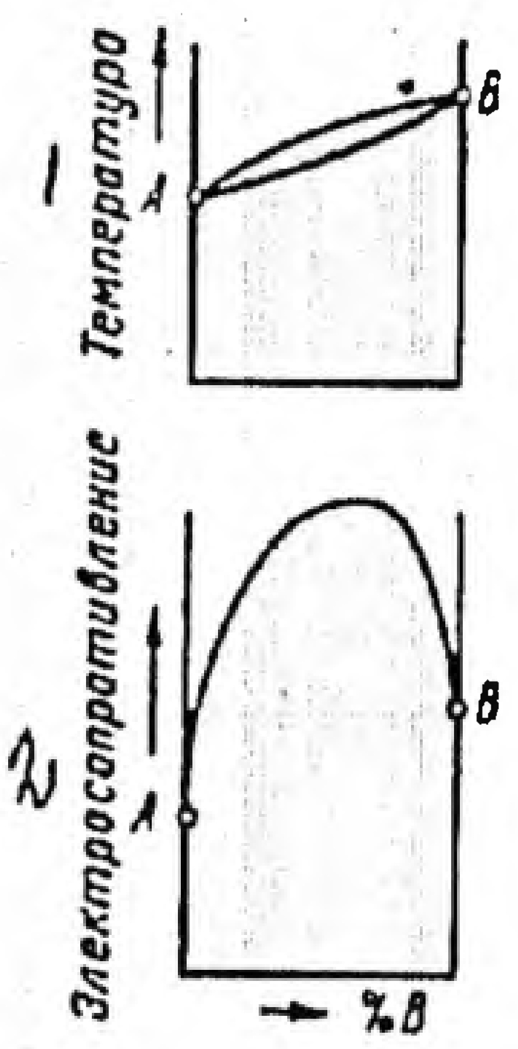

Fig. 48. Electrical resistance of pure components and alloys forming a continuous series of solid solutions (Kurnakov):

1 - temperature;
2 - electrical resistance.

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*From the standpoint of chemical composition, some of the subsequently listed oxidation-resistant alloys must be classified as steels in accordance with GOST 5632--51. However, in view of the fact that in practice and in the litera- they are generally designated as alloys having special physi- properties [23, 47, 49, 61], the authors have retained this term.

Alloys for heating elements must possess the following properties:

(1) high resistivity;
(2) a small temperature coefficient of electrical resistance (that is, there must be negligible change in electrical resistance with change in temperature):
(3) high oxidation resistance.

Iron or nickel represents the base of oxidation - resistant alloys; chromium, aluminum, and silicon are the basic alloying elements.

Chemical Composition, Forms of Semiproducts, And Basic Purpose

The chemical composition of oxidation-resistant alloys is given in Table 29, and the forms of semiproducts and basic purpose in Tables 30 and 31.

Technological Properties [7, 23, 28, 36, 46, 51, 72]

Alloy KhN60Yu. Standard heat treatment: quenching from 1200° in air. Can be satisfactorily press forged. Lends itself well to welding by all forms of welding.

Alloy KhN70Yu (E1652). Standard heat treatment: quenching from 1200° in air. Can be satisfactorily press forged. Produced in the form of thin and thick sheet material.

Alloy KhN38VT (E1703). Standard heat treatment: quenching from 1200° in air.

Alloy KhN75MBTYu (E1602). Standard heat treatment: quenching from 1050-1080° in air.

Alloy Kh20N80 (EZhN80). Possesses satisfactory satisfactory technological properties; permits press drawing into wire to a diameter of 0.1-0.3 mm.

Alloys Kh20N80T, KhN78T (E1435). Standard heat treatment: quenching from 1000-1150° in air. Weldability good in small thicknesses by argon-arc and resistance welding. The alloys lend themself well to deep drawing and other forms of plastic deformation in the cold state.

Alloy Kh20N80T3. Standard heat treatment: quenching from 1080° (holding for 8 hours) in air; aging at 700° for 16 hours; air cooling.

Alloy Kh13Yu4 (E160). Possesses satisfactory technological properties; produced in the form of strips and wire up to 0.2-0.3 mm in diameter.

The carbon content of this alloy, more than 0.2%, fosters the occurrence of microscopic defects in the alpha-hard solution in the drawing of wire; this may cause breaking of the latter when in use.

Alloys 0Kh17Yu5 (E1318), 0Kh23Yu5, 0Kh23Yu5A (E1292), 0Kh27Yu5A. These alloys possess satisfactory technological properties; they permit press drawing into wire in the hot and cold states.

A characteristic of all the iron-aluminum alloys is their tendency toward abrupt grain growth and drop in toughness at room temperature after heating to 900-1000°. Hence, straightening of heating coils of these alloys which have been inservice within the temperature range in question must be carried out after heating to 300-400°.

Oxidation Kinetics

Concise information is given in this section on the kinetics of oxidation of certain oxidation-resistant alloys based on nickel and iron. Table 32 gives a list of the alloys and the conditions under which the oxidation kinetics has been studied. Oxidation equations for alloys within the 900-1200° temperature range in air and in a furnace atmosphere, with an excess air coefficient, α, equalling 0.8 and 1.5 are given in Table 34.

It is to be seen that in the majority of cases, oxidation of each of the alloys listed follows the logarithmic or parabolic law, depending on the temperature and the composition of the gaseous atmosphere.

Table 33 gives data on the average rate of oxidation of chromium-nickel alloys, from which it is to be seen that in a slightly oxidizing atmosphere within the 900-1200° temperature range, alloy E1435 is the most highly oxidation-resistant of those listed. At 900° the oxidation of this alloy follows the logarithmic law in all three atmospheres; the oxide film on the alloy is, moreover, dense and strong, and is characterized by high protective properties. With elevation of the temperature to 1000°, the rate of oxidation of alloy E1435 in air rises sharply, oxidation in this case following the linear law. At 1200° oxidation of the alloy in all three atmospheres follows the logarithmic law, but in an atmosphere of air, the corrosion rate is high. Hence it is best to heat treat and employ the alloy in slightly oxidizing atmospheres.

The oxidation kinetics of alloy E1435 at 1000° in a furnace atmosphere with an excess air coefficient, α, equalling 0.8, 1.0 and 1.2 is shown in Fig 49. The test period corresponds to technological holding of the alloy in heating for rolling.

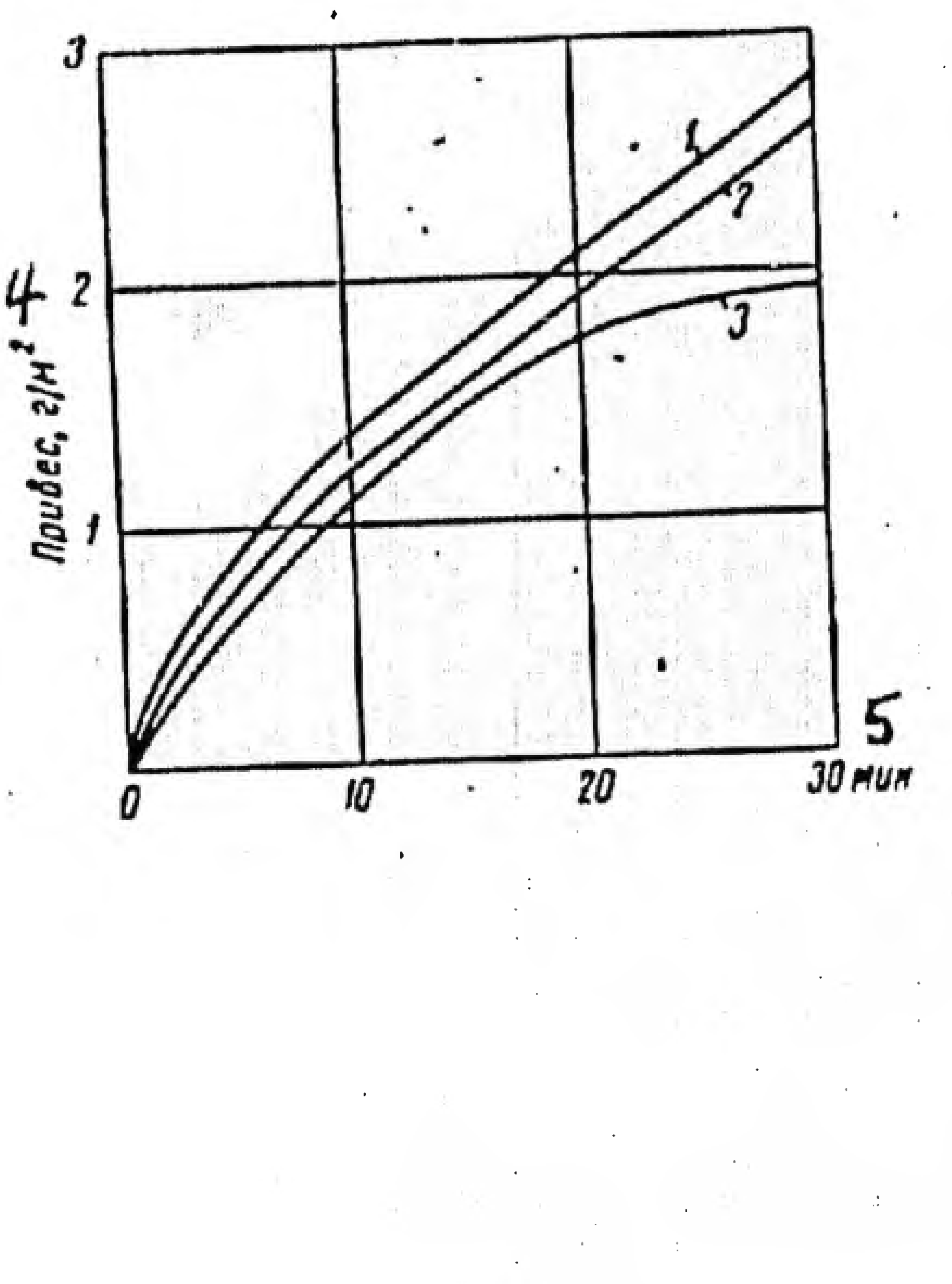


Fig. 49. Kinetics of oxidation of alloy E1435 in a furnace atmosphere at 1000° [32]:

1 - α = 0.8;
2 - α = 1.0;
3 - α = 1.2;
4 - weight gain, g/m^2;
5 - minutes.

Table 29

Chemical Composition of Oxidation-Resistant Alloys (According to GOST 5632-61, GOST-9232-59)

1 Марка сплава	2 Содержание элементов, %													3 Прочие элементы
	C	Si	Mn	Cr	Ni	Ti	Al	Mo	W	Fe	Nb	S	P	
5 ХН38ВТ (ЭИ703)	0,06–0,12	<0,8	<0,7	20–23	35–39	0,7–1,2	<0,5	—	2,8–3,5	4 Остальное	—	<0,02	<0,03	—
6 ХН60Ю (ЭИ559А)	<0,1	<0,8	<0,3	15–18	55–58	—	2,6–3,5	—	—	4 Остальное	—	<0,02	<0,02	<0,10Ba, <0,03Zr
7 ХН75МБТЮ (ЭИ602)	<0,1	<0,8	<0,4	19–22	4 Остальное	0,35–0,75	0,35–0,75	1,60–2,30	—	<8,0	0,90–1,30	<0,012	<0,02	—
8 ХН78Т (ЭИ435)	<0,12	<0,8	<0,7	19–22	4 Остальное	0,15–0,35	<0,15	—	—	<6,0	—	<0,015	<0,02	—
9 ХН60В (ЭИ868)	<0,1	<0,8	<0,5	23,5–26,5	4 Остальное	0,3–0,7	<0,5	—	13–16	<4,0	—	<0,013	<0,013	—
10 ХН70Ю (ЭИ652)	<0,1	<0,8	<0,3	26–29	4 Остальное	—	2,6–3,5	—	—	<1,0	—	<0,02	<0,02	<0,1Ba, <0,03Zr
11 ХН70 (ЭИ442)	<0,07	<0,8	<0,5	28–31	4 Остальное	—	<0,15	—	—	<5,0	—	<0,02	<0,02	—
12 Х15Н60 (ЭХН60)	<0,15	0,4–1,3	<1,5	15–18	4 55–61	—	<0,2	—	—	4 Остальное	—	<0,025	<0,035	—
13 Х20Н80 (ЭХН80)	<0,15	0,4–1,3	<0,7	20–23	75–78	—	<0,2	—	—	<1,0	—	<0,025	<0,03	—
14 1Х17Ю5 (ЭИ341)	<0,12	<1,2	<0,7	16–19	<0,6	—	4–6	—	—	4 Остальное	—	<0,03	<0,035	—
15 0Х17Ю5 (ЭИ318)	<0,06	<0,6	<0,7	16–19	<0,6	—	4–6	—	—	4 Остальное	—	<0,03	<0,035	—
16 1Х25Ю5 (ЭИ340)	<0,12	<1,2	<0,7	23–27	<0,6	—	4,5–6,5	—	—	4 Остальное	—	<0,03	<0,035	—
17 0Х25Ю5 (ЭИ292)	<0,06	<1,2	<0,7	23–27	<0,6	—	4,5–6,5	—	—	4 Остальное	—	<0,030	<0,035	—
18 Х13Ю4 (ЭИ60)	<0,15	<1,0	<0,7	12–15	<0,6	—	3,5–5,5	—	—	4 Остальное	—	<0,025	<0,035	—
19 0Х23Ю5	<0,06	0,7	<0,5	21,5–24,5	<0,6	—	4,5–5,5	—	—	4 Остальное	—	<0,02	<0,025	—
20 0Х23Ю5А	<0,05	<0,6	<0,3	21,5–23,5	<0,6	—	4,5–5,2	—	—	4 Остальное	—	<0,015	<0,015	—
21 0Х27Ю5А	<0,05	0,6	0,3	26–28	<0,6	—	5,0–5,8	—	—	4 Остальное	—	<0,015	<0,15	—
22 Х20Н80Т3	<0,08	<1,0	<0,5	19–23	4 Остальное	2,3–2,9	0,4–1,1	—	—	<2,5	—	<0,015	<0,02	—
23 Х20Н80Т	<0,12	<0,8	<0,7	12–21	4 Остальное	0,15–0,35	<0,15	—	—	<1,0	—	<0,05	<0,02	—
24 Хромаль (мегапир)	—	—	—	30	—	—	5	—	—	65	—	—	—	—
25 Новый мегапир	—	—	—	37,5	—	—	7,5	—	—	55	—	—	—	—

Translation of terms used in Table 29:

1 - brand of alloy; 2 - content of elements, %; 3 - other elements; 4 - balance; 5- KhN38VT (E1703); 6 - KhN60Yu (E1559A); 7 - KhN75MBTYu (E1602); 8 - KhN78T (E1435); 9 - KhN60V (E1868); 10 - KhN70Yu (E1652); 11 - KhN70 (E1442); 12 - Kh15N60 (EKhN60); 13 - Kh20N80 (EKhN80); 14 - 1Kh17Yu5 (E1341); 15 - OKh17Yu5 (E1318); 16 - 1Kh25Yu5 (E1340); 17 - Okh25Yu5 (E1292); 18 - Kh13Yu4 (E160); 19 - OKh23Yu5; 20 - OKh23Yu5A;* 22 - Kh20N80T3; 23 - Kh20N80T; 24 - Chromal (megapyr); 25 - new megapyr,*21 - OKh27Yu5A.

Table 30

Forms of Semiproducts Of Oxidation-Resistant Alloys And Standards Governing Delivered Output

Brand of alloy	Strips	Wire	Other forms of semiproducts
Kh15N60 (EKhN60)	GOST 2615-54 GOST 9232-59	GOST 2238-58 GOST 9232-59	--- ---
Kh20N80 (EKhN80)	GOST 2615-54 GOST 9232-59	GOST 2238-58 GOST 9232-59	--- ---
KhN78T (E1435)	GOST 2615-54 MPTU 4271-53	GOST 2238-58 ChMTU 5216-55	rods (MPTU 2632-49) bars (MPTU 2632-49) sections (ChMTU 5306-55, AMTU 361-56) sheets (ChMTU 3126-52, ChMTU 5363-55)
Kh20N80T3 (KhN80T, E1437)	GOST 2615-54 GOST 9232-59	GOST 2238-58 GOST 9232-59	rods (ChMTU 2961-51, ChMTU 3650-53 forgings (ChMTU 3587-53)
Kh13Yu4 (E160)	GOST 2615-54 GOST 9232-59	GOST 2238-58 GOST 9232-59	---
1Kh17Yu5 (E1341)	GOST 2615-54	GOST 2238-58	---
Okh17Yu5 (1318)	GOST 2615-54	GOST 2238-58	---
Okh25Yu5 (E1292)	GOST 2615-54	GOST 2238-58	---
1Kh25Yu5 (E1340) Okh23Yu5 OKh23Yu5A OKh27YU5A	GOST 2615-54 GOST 9232-59	GOST 2238-58 GOST 9232-59	---

Table 31

Use of Oxidation-Resistant Alloys (GOST 5632-61) [23, 47, 61, 72]

Brand of alloy	Temperature at which scale formation begins, °C	Operating temperature, special properties	Basic purpose
KhN38VT (E1703)	1050°	Operating temperature up to 950° under moderate stresses. Limited service life	Parts of gas pipeline systems
KhN60Yu (E1559A)	1200	Alloy characterized by high oxidation resistance in air atmosphere. Low resistance in sulfur-containing atmospheres SO_2, H_2S, and in nitrogen with low oxygen content. Operating temperature up to 1100° under slight stresses; up to 1200° with limited service life.	Parts of gas pipeline systems, installations, sheet parts of turbines
KhN75MBTYu (E1602)	1050	Operating temperature up to 950°. Limited service life.	
Kh20N80T (KhN78T, E1435)	1100	Operating temperature up to 1100° in air atmosphere. Unstable in sulfur-containing and carburizing atmospheres.	Parts of gas pipeline systems, burner liners of gas turbine combustion chambers, section shaped parts
KhN60V (E1868)	1100	Operating temperature up to 1100°. Limited service life (100-1000 hours). Unstable in atmospheres containing sulfur.	Sheet parts of turbines

Table 31 (Cont'd)

Brand of alloy	Temperature at which scale formation begins, °C	Operating temperature, special properties	Basic purpose
KhN70Yu (1652)	1200	Operating temperature up to 1100° under moderate stresses. Limited service life (100--1000 hours). Unstable in atmospheres containing sulfur.	Sheet parts, gas pipelines (may be used for the heating elements of resistors)
KhN70 (E1442)	1150	Unstable in atmospheres containing sulfur	Equipment
Kh15N60 (EKhN60)	1000	Operating temperature up to 1000°. Scale-resistant in oxidizing atmosphere, hydrogen, vacuum. Unstable in atmospheres containing sulfur	Heating elements of electric furnaces, hydrogenation plants, and furnaces for carburization
Kh20N80 (EKhN80)	1100	Operating temperature up to 1100°. Scale-resistant in oxidizing atmosphere, hydrogen, and vacuum	Heating elements of electric furnaces, parts of gas turbine combustion chambers, wire for depositing chamfers on exhaust valves of internal combustion engines
Kh20N80T3 (KhN80T, E1437)	1150	Alloy characterized by intensive precipitation hardening fostering improvement in strength and impairment of plastic properties. Impact toughness stable. Limited service life (up to 1000 hours) due to instability of mechanical properties, low plasticity, sensitivity to	Moving blades and disks of gas turbines, heating elements of electric furnaces

Table 31 (Cont'd)

Brand of alloy	Temperature at which scale formation begins, °C	Operating temperature, special properties	Basic purpose
Kh20N80T3 (KhN80T, E1437) (Cont'd)		embrittlement and stress concentration. Operating temperature 650-750°	
Kh13Yu4 (E1460)	850	Maximum operating temperature 850°. Scale-resistant in oxidizing atmosphere and atmospheres containing sulfur.	Wire for heating elements of household appliances and rheostats
1Kh17Yu5 (E1341)	900-1000	Maximum operating temperature 850°	Wire and strips for heating elements of electric furnaces
OKh17Yu5 (1318)	1000	Maximum operating temperature 1000°	Same, but with longer service life
1Kh25Yu5 (E1340)	1150-1200	Maximum operating temperature 1150°	Wire and strips for heating elements of large high-temperature electric furnaces
OKh25Yu5 (E1292)	1150-1200	Maximum operating temperature 1200°. Scale-resistant in oxidizing atmosphere and atmospheres containing sulfur	Same, but with longer service life
OKh23Yu5	1050-1100	Maximum operating temperature 1100°. Scale-resistant in oxidizing atmosphere and atmospheres containing sulfur	For heating elements of electric ovens
OKh23Yu5A	1050-1100		
OKh27Yu5A	1150-1200	Maximum operating temperature 1100°	
Chromal (megapyr)	---	Maximum operating temperature 1250°	
New megapyr	---	Maximum operating temperature 1350°	

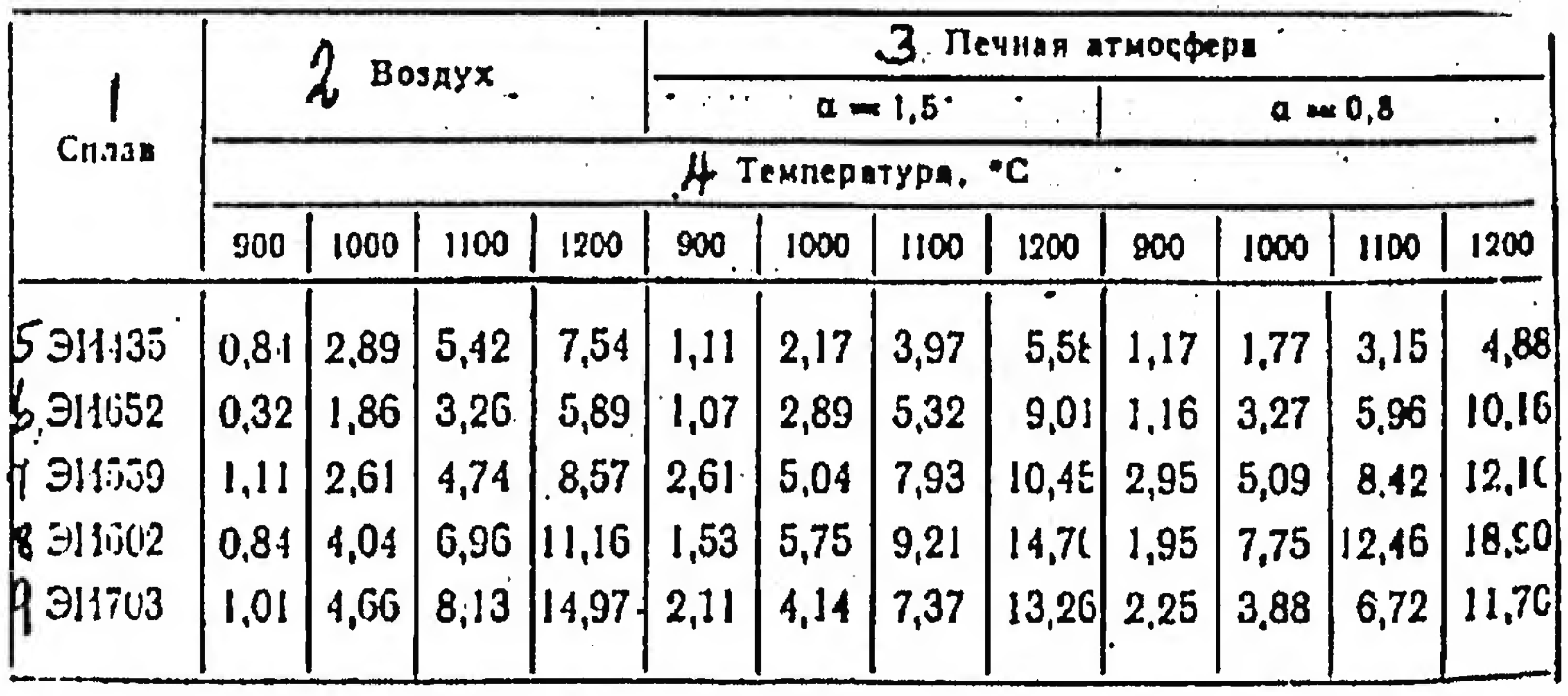
Table 32

Conditions Under Which Oxidation Kinetics Of Alloys Were Determined [1, 37]

Brand of alloy	Gaseous atmosphere	Temperature, °C	Test period, hours
KhN78T (E1435)	Air Furnace atmosphere	900--1200 900-1200	1; 20 minutes
KhN70Yu (1652)	" "	900-1200	1
KhN75MBYu (E1602)	" "	900-1200	1
KhN60Yu (E1559A)	" "	900-1200	1
KhN38VT (1703)	" "	900-1200	1
Kh20N80	Air	1100	100
Kh13Yu4	"	1100-1200	250
0Kh17Yu5	"	1100-1200	250
1Kh17Yu5	"	1100-1200	250
0Kh23Yu5	"	1100-1200	250
0Kh25Yu5	"	1100-1200	250
1Kh25Yu5	"	1100-1200	250

Table 33

Average Rate Of Oxidation Of Alloys (mg/m^2 • h) in time τ = 1 h 1



1 Сплав	2 Воздух				3 Печная атмосфера							
					α = 1,5				α = 0,8			
	4 Температура, °C											
	900	1000	1100	1200	900	1000	1100	1200	900	1000	1100	1200
5 ЭИ435	0,84	2,89	5,42	7,54	1,11	2,17	3,97	5,5	1,17	1,77	3,15	4,88
6 ЭИ652	0,32	1,86	3,26	5,89	1,07	2,89	5,32	9,01	1,16	3,27	5,96	10,16
7 ЭИ559	1,11	2,61	4,74	8,57	2,61	5,04	7,93	10,45	2,95	5,09	8,42	12,10
8 ЭИ602	0,84	4,04	6,96	11,16	1,53	5,75	9,21	14,70	1,95	7,75	12,46	18,90
9 ЭИ703	1,01	4,66	8,13	14,97	2,11	4,14	7,37	13,26	2,25	3,88	6,72	11,70

1 - alloy; 2 - air; 3 - furnace atmosphere; 4 - temperature, °C; 5 - E1435; 6 - E1652; 7 - E1559; 8 - E1620; 9 - E1703.

The oxidation of alloys E1652 and E1559 in air and in a furnace atmosphere with α = 1.5 and 0.8 in the 900-1200° temperature range follows the logarithmic law.

It is recommended that these alloys be heat treated and used in air. Alloy E1559 may be utilized as a substitute for alloy E1435 in operation in air at temperatures above 1000°.[1]

In oxidation resistance alloy E1602 is inferior to alloy E1435. The kinetics of oxidation of this alloy at 900° in air is determined by the parabolic equation, and in a furnace atmosphere with α = 0.8 and 1.5 by the logarithmic equation. With elevation of the temperature to 1200°, oxidation of the alloy becomes subject to the parabolic law. It is advisable to conduct heat treatment of the alloy in oxidizing atmospheres.

Table 34

Oxidation Equations Of Certain Alloys, $\Delta g = f(\tau)$, (Δg in g/m^2, τ in minutes) [1]

1 Марка сплава	2 Температура °С	3 Воздух	4 Продукты горения газа	
			$\alpha = 1,5$	$\alpha = 0,8$
5 ХН78Т (ЭИ435)	900 1000 1100 1200	$\Delta g = 0,71 \lg \tau - 0,46$ $\Delta g^{1,03} = 0,07\tau$ $\Delta g^{1,85} = 0,38\tau$ $\Delta g = 4,30 \lg \tau - 0,19$	$\Delta g = 0,67 \lg \tau - 0,10$ $\Delta g = 1,25 \lg \tau - 1,25$ $\Delta g^{1,68} = 0,16\tau$ $\Delta g = 3,20 \lg \tau - 0,30$	$\Delta g = 0,70 \lg \tau - 0,10$ $\Delta g = 1,06 \lg \tau - 0,15$ $\Delta g^{1,94} = 0,15\tau$ $\Delta g = 3,00 \lg \tau - 0,60$
6 ХН70Ю (ЭИ652)	900 1000 1100 1200	$\Delta g = 0,30 \lg \tau - 0,20$ $\Delta g = 1,10 \lg \tau - 0,04$ $\Delta g = 1,79 \lg \tau - 0,01$ $\Delta g = 3,16 \lg \tau + 0,03$	$\Delta g = 0,74 \lg \tau + 0,17$ $\Delta g = 1,50 \lg \tau + 0,05$ $\Delta g = 2,80 \lg \tau$ $\Delta g = 5,20 \lg \tau - 0,30$	$\Delta g = 0,77 \lg \tau + 0,15$ $\Delta g = 1,66 \lg \tau + 0,10$ $\Delta g = 3,80 \lg \tau - 0,60$ $\Delta g = 7,00 \lg \tau - 1,8$
7 ХН75МБТЮ (ЭИ602)	900 1000 1100 1200	$\Delta g^{3,33} = 0,01\tau$ $\Delta g^{2,00} = 0,26\tau$ $\Delta g^{1,92} = 0,64\tau$ $\Delta g^{1,67} = 1,00\tau$	$\Delta g = 0,71 \lg \tau + 0,22$ $\Delta g^{2,37} = 1,00\tau$ $\Delta g^{2,37} = 2,95\tau$ $\Delta g^{2,30} = 7,42\tau$	$\Delta g = 0,94 \lg \tau + 0,20$ $\Delta g = 3,89 \lg \tau + 0,80$ $\Delta g^{2,25} = 3,27\tau$ $\Delta g^{2,50} = 25,0\tau$
8 ХН38ВТ (ЭИ703)	900 1000 1100 1200	$\Delta g = 0,55 \lg \tau$ $\Delta g^{2,43} = 0,36\tau$ $\Delta g^{2,06} = 1,27\tau$ $\Delta g^{1,84} = 2,05\tau$	$\Delta g = \lg \tau$ $\Delta g^{2,25} = 0,33\tau$ $\Delta g^{2,02} = 0,87\tau$ $\Delta g^{1,88} = 1,80\tau$	$\Delta g = 1,11 \lg \tau + 0,10$ $\Delta g^{2,20} = 0,28\tau$ $\Delta g^{2,00} = 0,69\tau$ $\Delta g^{2,00} = 2,00\tau$
9 ХН60Ю (ЭИ559)	900 1000 1100 1200	$\Delta g = 0,50 \lg \tau + 0,50$ $\Delta g = 1,25 \lg \tau + 0,50$ $\Delta g = 2,47 \lg \tau + 0,35$ $\Delta g = 4,55 \lg \tau + 0,55$	$\Delta g = 1,40 \lg \tau + 0,18$ $\Delta g = 3,00 \lg \tau - 0,20$ $\Delta g = 4,35 \lg \tau + 0,10$ $\Delta g = 5,70 \lg \tau + 0,20$	$\Delta g = 1,67 \lg \tau$ $\Delta g = 3,00 \lg \tau$ $\Delta g = 4,70 \lg \tau$ $\Delta g = 7,30 \lg \tau - 0,80$

1 - brand of alloy; 2 - temperature, °C; 3 - air; 4 - gas combustion products; 5 - KhN78T (E1435); 6 - KhN70Yu (E1652); 7 - KhN75MBTYu (E1602); 8 - KhN38VT (E1703); 9 - KhN60Yu (E1559).

Oxidation of alloy E1703 in all three atmospheres at 900° follows the logarithmic law, and at temperatures of 1000-1200° the parabolic law; the exponents of the equations decrease with elevation of the temperature. It is recommended that heat treatment of the alloy be conducted in a slightly oxidizing atmosphere with an excess air coefficient = 0.8 at temperatures no higher than 900°, since cracks form in the oxide film in the event of heating above this temperature.

Fig. 50 shows the kinetics of oxidation of chromium-nickel alloy Kh20N80 at 1100° in air. Oxidation of the alloy proceeds relatively slowly in time.

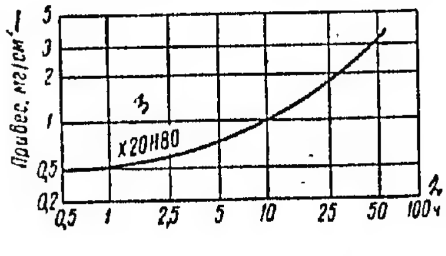


Fig. 50. Kinetics of oxidation of alloy Kh20N80 in air at 1100° [66]:

1 - weight gain, mg/cm^2;
2 - hours;
3 - Kh20N80.

The oxidation rate of wire of chromium-nickel alloys of varying chromium content in comparison with the oxidation rate of pure nickel at various temperatures is shown in Fig. 51. The oxidation rate of chromium-nickel alloys is lower than that of pure nickel. Moreover, the higher the chromium content of the alloy, the slower is its oxidation rate.

For operation at high temperatures, in particular for electric heaters, use is made of Fe-Cr-Al alloys. Fig. 13 illustrates the oxidation rate of iron-aluminum alloys with various chromium contents. When the alloys contain 5-10% aluminum, the addition of more than 20% chromium presents no advantages whatever.

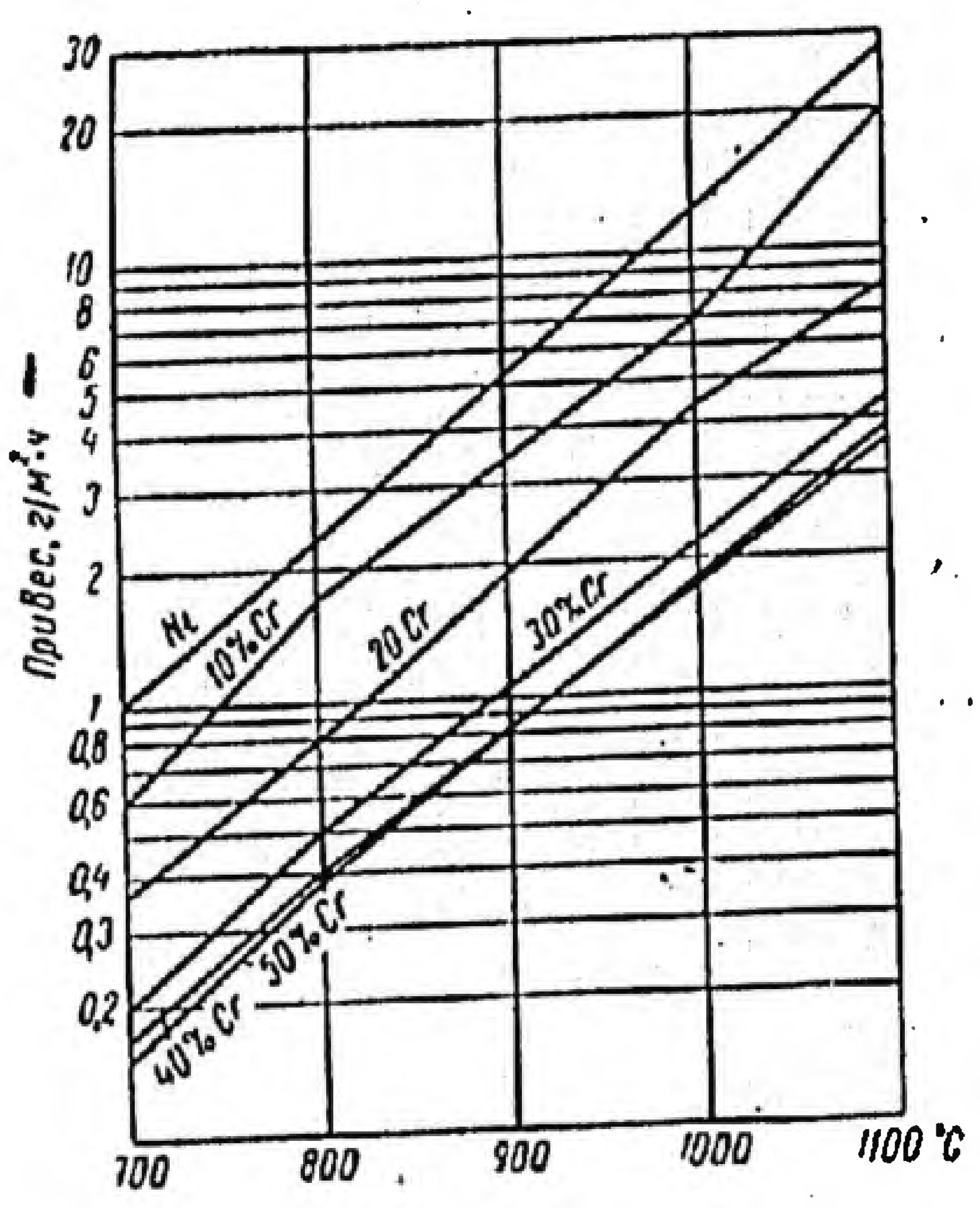


Fig. 51. Rate of oxidation of nickel in chromium-nickel alloys at various temperatures [76]:
1 - weight gain, g/m^2 . h.

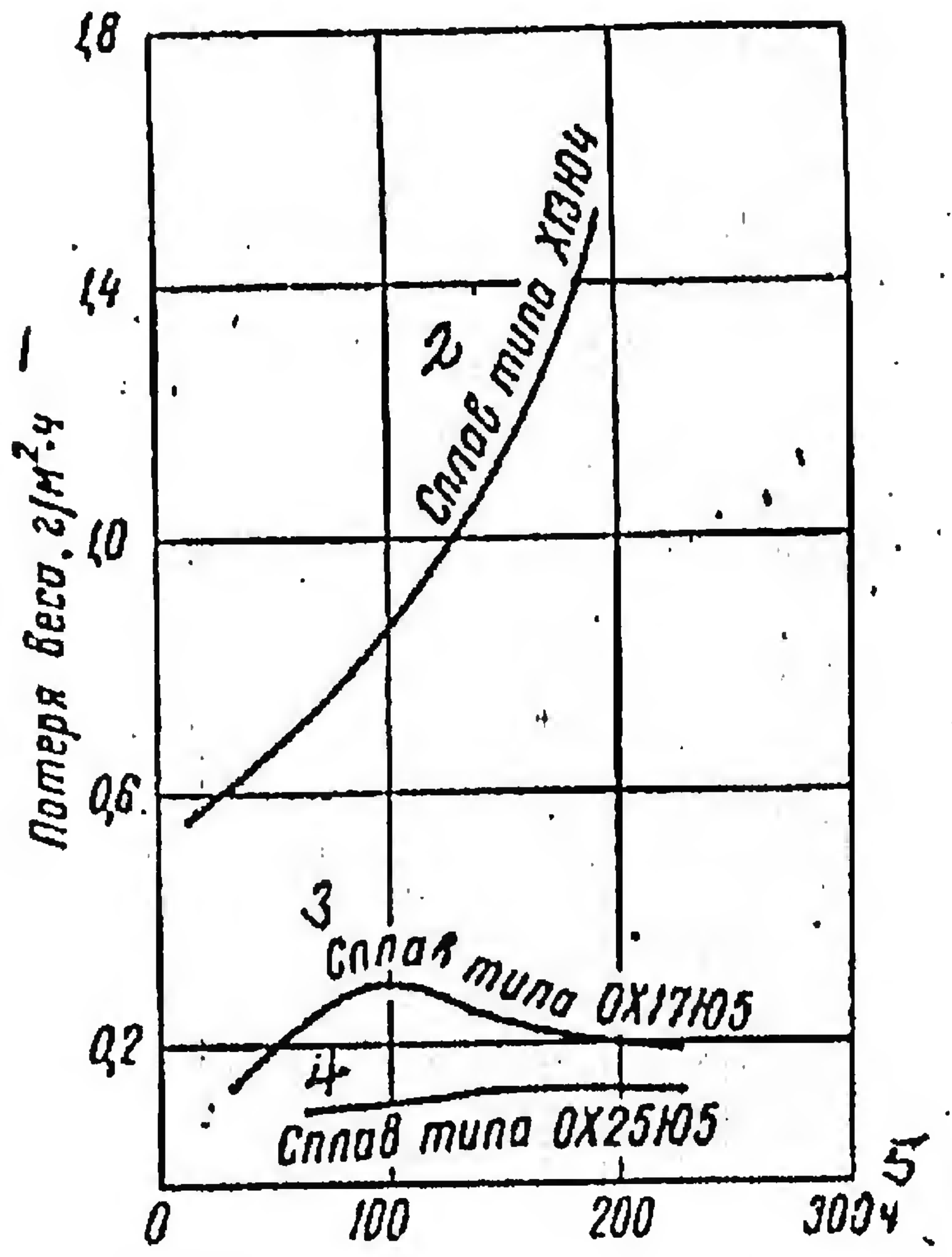


Fig. 52. Kinetics of oxidation of Fe-Cr-Al alloys in air at temperatures of 1100-1200° [37]:

1 - weight loss, g/m^2 . h;
2 - alloy of Kh13Yu4 type;
3 - alloy of Okh17Yu5 type;
4 - alloy of Okh25Yu5 type;
5 - hours.

The kinetics of oxidation iron-chromium-aluminum alloys in air at temperatures of 1100-1200° is depicted in Fig. 52, from which it is to be seen that the lowest oxidation in time is that to which are subjected alloys of the Kh25Yu5 type having a high chromium content and 5% Al; the weight gain of this alloy is negligibly small and the curve of oxidation in time up to 250 hours runs nearly parallel to the X-axis.

The kinetics of oxidation of certain resistance alloys in a carburizing atmosphere is shown in Fig. 53, from which it is to be seen that Fe-Cr-Al alloys are stabler in a carburizing atmosphere than are chromium-nickel alloys of the Kh20N80 type.

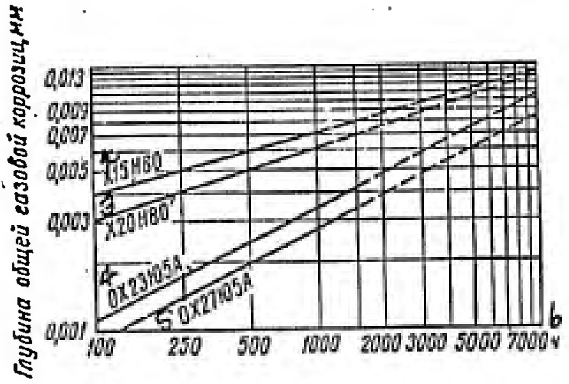


Fig. 53. Kinetics of oxidation of certain alloys having high electrical resistance in a carburizing atmosphere at 1050° [33] Composition of carburizing atmosphere: CO_2 — 0.1-0.2%; CO — 30-35%; H_2 — 55-60%; CH_4 — 0.1-0.5%; N_2 — balance;

1 - depth of general gas corrosion, mm;
2 - Kh15N60;
3 - Kh20N80;
4 - OKh23Yu5A;
5 - OKh27Yu5A;
6 - hours.

Corrosion Resistance In Gaseous Atmospheres

As is shown by Table 35, alloys with a high nickel content are resistant to the action of oxidizing and reducing atmospheres which do not contain sulfur compounds. High-nickel alloys corrode rapidly in atmospheres containing sulfur. Better results from the standpoint of resistivity to oxidation in atmospheres containing sulfur are exhibited by alloys having a lower nickel content and a higher chromium content.

The chromium content of high-nickel alloys which ensures the best corrosion resistance for the latter in air at temperatures up to 1000° is relatively low, ranging from 12 to 16%.

In hydrogen iron-nickel-chromium alloys undergo intensive corrosion even at relatively low temperatures. (Table 36).

Given in Table 37 are data on the life of wire of certain alloys employed in electric heaters.

It is to be seen from Table 37 that wire of nichrome of brand Kh20N80 is characterized by the longest life in the atmospheres investigated. Among the FE-Cr-Ni alloys the more long-lived ones in the gaseous atmospheres listed are alloys with a lower iron content; the life of wire of Fe-Cr-Al alloys in oxidizing atmospheres is longer than that of the Fe-Cr-Ni alloys tested.

Table 35

Oxidation Of Fe-Cr-Ni Alloys in Various Atmospheres [69]

1 Сплав, %		2 Привес, мг/дм²·сутки					
		3 SO_2 при температурах			O_2, CO_2, H_2O * 4 при температурах		
Cr	Ni	800°	900°	1000°	800°	900°	1000°
11	35	41	42	790	200—730	615—1170	1165—1930
12	60	500	5500	9100	23—41	30—49	115—180

---

5 * Средняя скорость окисления сплавов в кислороде, двуокиси углерода и водяном паре.

Translation of items in Table 35: 1 - alloy, %; 2 - weight gain, mg/dm^2 · 24 hours; 3 - SO_2, at temperatures of; 4 - at temperatures of; 5 - average rate of oxidation of alloys in oxygen, carbon dioxide, and water vapor.

Table 36

Oxidation Of Fe-Cr-Ni Alloys In Hydrogen Sulfide[69]

1 Сплав, %			2 Привес, $г/м^2 \cdot ч$ при температурах	
Cr	Ni	Fe	480°	650°
12	60	3 Остальное	—	71,2
14,7	35		10	—
13,8	62		12,1	—
18	75		24,2	—

1 - alloy, %; 2 - weight gain, g/m^2 · h, at temperatures of; 3 - balance.

The behavior of resistance alloys in a carburizing atmosphere is of interest. Thus, iron-chromium-aluminum alloys OKh27Yu5 and OKh23Yu5 are not carburized in a carburizing atmosphere and do not undergo intercrystalline corrosion; a dense protective film of the spinel type is formed on their surface.

Chromium-nickel alloys Kh20N80 and Kh15N60 are less resistant in a carburizing atmosphere than are Fe-Cr-Al alloys. These alloys absorb carbon and gases and are oxidized to a greater depth. They do not undergo intercrystalline corrosion. The kinetics of oxidation of these alloys in a carburizing atmosphere is shown in Fig. 53.

The specific electrical resistance of these alloys is virtually unchanged in a carburizing atmosphere.

Table 37

Life Of Wire Of Certain Alloys For Electric Motors When Heated In Various Gaseous Atmospheres [69]

1 Сплав, %				2 Температура проволоки, °C	3 Долговечность, ч						
Ni	Cr	Al	Fe		4 Воздух	CO_2	N_2	5 Городской газ	O_2	H_2	6 Водяной газ
80	20	—	7 Остальное	1050	153	205	167	130	132	>300	>400
60	18,5	—		1050	71	101	118	137	52	>300	>360
35	20	—	»	1050	51	47	71	—	44	>300	143
—	30	5	»	1200	123	142	64	106	138	>300	60

Примечания: 1. Состав газов:
Азот . . . . 2% O_2
Городской газ . . . 53% H_2, 1,7% CO_2, 3,85% SO_2, 30,3% CH_4
Водяной газ . . . 49% H_2, 40,5% CO, 4% CO_2

2. Условия испытаний: спирали из проволоки диаметром 0,4 мм попеременно нагревались в указанных средах с интервалом в 2 мин до тех пор, пока некоторые участки проволоки не превращались целиком в окалину.

Translation of items in Table 37: 1 - alloy, %; 2 - wire temperature, °C; 3 - life, hours; 4 - air; 5 - town gas; 6 - water gas; 7 - balance. Remarks:

Remarks: 1. Composition of gases:

Nitrogen: 2% O_2

Town gas: 53% H^2; 1.7% CO_2; 3.85% SO_2, 30.3% CH_4

Water gas: 49% H_2 , 40.5% CO, 4% CO_2

2. Test conditions: coils of wire 0.4 mm in diameter heated alternately in the atmospheres indicated at 2-minute intervals until certain sections of the wire were completely converted into scale.

It is recommended that alloys 0Kh27Yu5 and 0Kh23Yu5 be employed for the heaters of periodic carburizing furnaces.

For structural reasons alloy Kh20N80 may also be employed in special cases [33].

Metals And other Materials Employed For Heating Elements

Metal heating elements of alloys are generally utilized for furnaces operating at temperatures up to 1300°. For furnaces and installations with a higher operating temperature (up to 2000° and above) use is made of heating elements of refractory metals: molybdenum, tungsten, and tantalum.

The heaters must operate in a vacuum or in a special gaseous atmosphere, since these metals undergo intensive oxidation and evaporation when heated in air.

Data on the relative evaporation rate of molybdenum, tungsten, and tantalum at temperatures of 1530-2530° are given in Table 38, from which it follows that the rate of evaporation of these metals rises sharply with elevation of the temperature. The greatest evaporation is observed with molybdenum, and the least with tungsten.

Table 39 shows the stability of heating elements of molybdenum, tungsten, and tantalum in furnaces with varying atmospheres. The temperature range of operation of heating elements of the metals in question is established in practice on the basis of the data in this table, in keeping with the furnace atmosphere.

The stability of operation of heating elements of molybdenum, tungsten, and tantalum depends largely also on the furnace material with which the element comes in contact.

Table 38*

Rate Of Evaporation At High Temperatures Of Certain Metals Employed For Heating Elements [77]

Translation of items in Table 38: 1 - metal; 2 - molybdenum; 3 - tungsten; 4 - tantalum; 5 - evaporation rate (mg/cm² · h) at temperatures of; 6 - 180, very high for technical use.

*See next page

1 Металл	5 Скорость испарения ($мг/см^2 \cdot ч$) при температурах					
	1530°	1730°	1930°	2130°	2330°	2530°
2 Молибден	$3{,}1 \cdot 10^{-4}$	$3{,}6 \cdot 10^{-2}$	6 180, очень высокая для технического применения			
3 Вольфрам	$1{,}3 \cdot 10^{-10}$	$5{,}3 \cdot 10^{-8}$	$7{,}5 \cdot 10^{-6}$	$4{,}6 \cdot 10^{-4}$	$1{,}4 \cdot 10^{-2}$	0,27
4 Тантал	—	$5{,}9 \cdot 10^{-6}$	$3{,}5 \cdot 10^{-4}$	$1{,}1 \cdot 10^{-2}$	$2 \cdot 10^{-1}$	2,5

Table 40 gives data on the behavior of heaters of molybdenum, tungsten, or tantalum when in contact with certain refractory materials.

A number of technical specifications must be observed for normal operation of industrial heating furnaces. For instance, molybdenum heaters must be manufactured from wire or strips of large cross-section, since with small cross-sections slight local reduction in cross-section leads to sharp increase in current density, local heating, and failure of the metal.

Insofar as possible, molybdenum heaters should not come in contact with the ceramics of the furnace; the electrical contacts of the heaters should be cooled with water.

Since molybdenum undergoes very intensive oxidation, heaters of this metal may operate only in a protective atmosphere (hydrogen, cracking ammonia, partly burned illuminating gas, inert gases) or in a vacuum greater than 10^{-2} mm Hg. The maximum operating temperature of furnaces having molybdenum heaters is 1600-1700°.

Molybdenum heaters are employed chiefly in furnaces for sintering metal powders, muffle furnaces for brazing and annealing, and in certain smelting units to obtain copper, uranium, and other metals.

Tungsten is difficult to machine; hence heaters of this metal are manufactured in the form of round rods or curved pipes.

Tungsten heaters may be employed only in a reducing or inert atmosphere, as well as in a vacuum greater than 10^{-2} mm Hg. The maximum operating temperature of tungsten heaters reaches 2000-2500°. Insofar as possible, the contacts of tungsten heaters should be cooled with water. The design of the heating furnaces must ensure that there will be no contact between the tungsten heaters and the ceramics.

Tubular or spiral heating elements of varying shape can easily be manufactured from tantalum.

Unlike molybdenum and tungsten heaters, ones of tantalum may be employed in furnaces with a vacuum greater than 10^{-4} mm Hg. In view of the high gas-absorption capacity of tantalum, its use in atmospheres containing hydrogen, oxygen, nitrogen, and carbon causes embrittlement due to the formation of nitrides, carbides, oxides, or hydrides.

Table 39

Stability Of Heating Elements In Furnaces With Various Atmospheres [77]

Furnace atmosphere	Material of heating elements		
	Molybdenum	Tungsten	Tantalum
Air or gases containing molybdenum	Oxidation begins at temperature above 400-500°; heavy evaporation at temperature above 800°	Oxidation begins at temperature above 500°; heavy oxidation at temperature above 1200°	Oxidation and formation of nitrides at temperature above 500°
Dry hydrogen (less than 0.5 g water per m^3)	Stable to melting point		Formation of hydride at 400-800°; above this temperature stable to melting point; surface oxidation
Moist hydrogen (less than 20 g water per m^3)	Stable to 1400°; growth of metal needles on surface is observed above this temperature		Formation of hydrides and heavy oxidation at temperature above 450°
Cracking ammonia (dry)	Stable to melting point		Formation of nitrides and hydrides at temperature above 400-450°; complete nitriding above this temperature
Inert gas (argon, helium)	Stable to melting point		
Vacuum above 10^{-2} mm Hg	Stable to 1700°	Stable to 2000°	Occurrence of embrittlement due to gas absorption
Vacuum above 10^{-4} mm Hg	Heavy evaporation at temperatures above 1800°	Heavy evaporation at temperatures above 2400°	Heavy evaporation at temperatures above 2200°
Partly burned ammonia (dry)	Stable to melting point		Same as with cracking ammonia
Partly burned illuminating gas, generator gas, etc.	Stable to 1300°; surface carburization above 1200°	Stable to 1400°; surface carburization above 1300°	Formation of nitrides; carbides, and hydrides; embrittlement

Table 40

Stability Of Certain Heating Elements Of High-Temperature Furnaces When In Contact With Various Refractory Materials [77]

Refractory furnace material	Stability of heating element material		
	Molybdenum	Tungsten	Tantalum
Graphite	Heavy carbide formation at temperatures above 1200°	Heavy carbide formation at temperatures above 1400°	Heavy carbide formation at temperatures above 1000°
Al_2O_3	Up to 1900°	Up to 1900°	Up to 1900°
BeO	Up to 1900°*	Up to 2000°*	Up to 1600°*
MgO	Up to 1800°*	Heavy evaporation of magnesium oxide up to 2000°*	Up to 1800°*
ZrO_2	Heavy evaporation of Mo up to 1900°*	Up to 1600°*	Up to 1600°*
Magnesite brick	Up to 1600°	Up to 1600°	Up to1500°
Th ThO_2	Up to 1900°*	Up to 2200°*	Up to 1900°
Sillimanite	Up to 1700°	Up to 1700°	Up to 1600°

* In a vacuum of 10^{-4} mm Hg; in a protective gaseous atmosphere, the stability of the material is approximately 100-200°.

The maximum operating temperature of tantalum heaters is 2200°.

It should be noted that niobium possesses properties similiar to those of tantalum, but it is limited at the present time due to its high cost.

In addition to metals and alloys, non-metallic materials such as carborundum (of the silite type), molybdenum disilicide, etc., are also employed for the heating elements of electric furnaces.

Heaters of the materials in question are characterized by extremely high electrical resistance and ensure an operating temperature for the furnace of 1500° and above.

Table 41

Physical Properties Of Materials Employed For Heating Elements [59, 72, 79, 87, 100]

1 Наименование материала	Удельный вес, г/см³ 2	3 Удельное электросопротивление при 20°, ом·мм²/м	4 Коэффициент линейного расширения при 20°·10⁶	5 Теплопроводность, ккал/м·ч·°C	6 Теплоемкость, ккал/г·°C	7 Максимальная рабочая температура °C	Удельная поверхностная нагрузка вт/см² 8
9 Молибден	10,28	0,05	5,2	0,35	0,065	1700	—
10 Вольфрам	19,3	0,05	4,5	0,47	0,034	2500	—
11 Тантал	16,5	0,12	6,5	0,13	0,033	2200	—
12 Сплав 0Х17Ю5 (ЭИ318)	7,0—7,2	1,3—1,5	14,5—15,0	—	—	<1000	—
13 Сплав 0Х25Ю5 (ЭИ292)	6,9—7,2	1,4—1,6	14,5—15,0	—	—	<1200	—
14 Сплав Х13Ю4 (ЭИ60)	7,4	1,25—1,35	—	—	—	<850	—
15 Сплав 1Х17Ю5 (ЭИ341)	7,0—7,2	1,15—1,25	14,5—15,1	—	—	<850	—
16 Сплав 1Х25Ю5 (ЭИ340)	7,0—7,2	1,25—1,45	14,5—15,5	—	—	<1150	—
17 Сплав Х15Н60 (ЭХН60)	8,4	1,0—1,15	—	—	—	<1000	—
18 Сплав Х20Н80	8,4	1,10—1,20	14,0	—	0,105	<1100	—
19 Сплав хромаль (мегапир)	—	1,6	—	—	—	1250	—
20 Сплав новый мегапир	—	1,8	—	—	—	1350	—
21 Карборундовые 1 (типа силит); состава: 94,4% SiC, 3,6% SO_2, 0,3% C, 0,2% Al, 0,6% Fe, 0,3% Si, 0,6% CaO + MgO	3,27—3,30	1000—2000	—	23 20 при 1000—1400°	0,170	1400	1,3
22 Дисилицид молибдена $MoSi_2$ (36,9% Si)	6,02	0,25	5,1	46,5	0,092	1500 24 и выше	50—60

1 - designation of material; 2 - specific gravity, g/cm^3; 3 - specific electric resistance at 20^o, ohm • mm^3/m; 4 - linear expansion coefficient at 20^o • 10^6; 5 - thermal conductivity, kcal/m • h • ^{o}C; 6- heat capacity, kcal/g • ^{o}C; 7 - maxiumum operating temperature, ^{o}C; 8 - specific surface load, wt/cm^2; 9 - molybdenum; 10 - tungsten; 11 - tantalum; 12 - alloy OKh17Yu5 (EI318); 13 - alloy OKh25Yu5 (EI292); 14 - alloy Kh13Yu4 (EI60); 15 - alloy 1Kh17Yu5 (EI341); 16 - alloy 1Kh25Yu5 (EI340); 17 - alloy Kh15N60 (EKhN60); 18 - alloy Kh20N80; 19 - chromal (megapyr) alloy; 20 - new megapyr alloy; 21 - carborundum 1 alloys (silite type); composition: 94.4% SiC; 3.6% SO_2, 0.3% C, 0.2% Al, 0.6% Fe, 0.3% Si, 0.6% CaO MgO; 22 - Molybdenum disilicide $MoSi_2$ (36.9% Si); 23 - at; 24 - and above.

Molydbenum disilicide withstands an electrical load of 50-60 wt/cm^2. No other heating element can withstand such a load [67].

The physical properties of metallic and non-metallic materials employed for heating elements are given in Table 41. It is to be seen from this table that the lowest specific electrical resistance is possessed by molybdenum, tungsten, and tantalum (10-20 less than alloys).

Ferrite alloys alloyed with aluminum, of the OKh25Yu5 type, as was pointed out earlier, are also employed for the heaters of carburizing furnaces due to their high resistivity to carburization and the absence of a tendency toward intercrystalline corrosion [33].

The data of Table 42 characterize the change in the specific electrical resistance of certain metals and alloys as a function of temperature. Such alloys as Kh15N60 are characterized by a stable electrical resistance value over the temperature range from 0 to 1000°.

Table 42

Change In Specific Electrical Resistance (ohm • mm^2/m) As A Function of Temperature [72, 77]

1 Материал нагревателя	2 Температура, °C							
	0	200	400	600	800	1000	1500	2000
3 X15H60	1,13	1,16	1,18	1,20	1,21	1,23	—	—
4 X20H80	1,10	1,12	1,15	1,15	1,15	1,15	—	—
5 Молибден	0,05	—	—	—	—	0,27	0,43	0,60
6 Вольфрам	0,05	—	—	—	—	0,33	0,50	0,66
7 Тантал	0,12	—	—	—	—	0,54	0,72	0,87

1 - heater material;
2 - temperature; °C;
3 - Kh15N60;
4 - Kh20N80;
5 - molybdenum;
6 - tungsten;
7 - tantalum.

Unlike alloys, the metals molybdenum, tungsten, and tantalum increase the electrical resistance fivefold when heated to 1000° and seven-to twelvefold when heated to 2000°.

4. OXIDATION-RESISTANT CAST IRONS

The oxidation resistance of cast iron is defined as its capacity to resist growth (not more than 0.2%) and scale formation (not more than 0.5 $g/m^2 \cdot h$) at a specified temperature for 150 hours.

As is known, oxidation-resistant cast irons are medium- and high-alloy cast irons. The basic alloying components of these cast irons include chromium, silicon, aluminum, nickel, and others.

The chemical composition of oxidation-resistant cast irons is shown in Table 43.

The properties of cast irons, including oxidation-resistant ones, are determined by their structure as well as by their chemical composition. As may be seen from Table 44, in structure, oxidation-resistant cast irons may be ferritic, carbide-ferritic, pearlitic, or austenitic.

Tables 45-47 give the physical and mechanical properties of oxidation-resistant cast irons, as well as the comparative indices of their oxidation resistance in an atmosphere of air and sormite, the structures of which consist of alloyed ferrite, complex carbides, and carbide eutectic. These cast irons are characterized by the highest hardness. They are of low machinability. Thus, sormite can be machined only by means of abrasives.

The shape of the graphite inclusions exerts an appreciable influence on the physical and strength properties of oxidation-resistant cast irons.

Table 43

Chemical Composition Of Oxidation-Resistant Cast Irons (GOST 7769-63) [23, 55]

1 Наименование чугуна	2 Марка чугуна	3 Содержание элементов, %							
		C	Si	Mn	P	S	Cr	Ni	Al
4 Хромистый	11 ЖЧХ-0,8	3,0—3,9	1,5—2,5	16 До 1,0	16 До 0,3	16 До 0,12	0,5—1,0	—	—
	11 ЖЧХ-1,5	3,0—3,9	1,7—2,7	16 До 1,0	16 До 0,3	16 До 0,12	1,1—1,9	—	—
	11 ЖЧХ-2,5	3,0—3,9	2,8—3,8	16 До 1,0	16 До 0,3	16 До 0,12	2,0—2,7	—	—
	11 ЖЧХ-30	2,4—3,0	1,0—2,0	16 До 0,7	16 До 0,1	16 До 0,08	28—32	—	—
5 Кремнистый с пластинчатым графитом	12 ЖЧС-5,5	2,4—3,2	5,0—6,0	0,5—1,2	16 До 0,3	16 До 0,12	0,5—0,9	—	—
6 Кремнистый с шаровидным графитом	13 ЖЧСШ-5,5	2,5—3,2	5,0—6,0	До 0,7	16 До 0,2	16 До 0,03	До 0,2	—	—
7 Алюминиевый с пластинчатым графитом	14 ЖЧЮ 22	1,6—2,5	1,0—2,0	0,4—0,8	16 До 0,2	16 До 0,08	—	—	19 25
8 Алюминиевый с шаровидным графитом	15 ЖЧЮШ-22	1,6—2,5	1,0—2,0	0,4—0,8	16 До 0,2	16 До 0,05	—	—	19—25
9 Никросилал	—	1,8—2,0	5,0—7,0	0,5—1,0	16 До 0,12	16 До 0,12	1,8—5,0	16—20	—
10 Сормайт	—	2,5—3,5	2,5—3,5	1,0—1,5	16 До 0,08	16 До 0,08	28—35	3—5	—

1- designation of cast iron; 2 - brand of cast iron; 3 - content of elements, %; 4 - chromium; 5- silicon with lamellar graphite; 6- silicon with spheriodal graphite; 7 - aluminum with lamellar graphite; 8 - aluminum with spheroidal graphite; 9 - nicrosilal; 10 - sormite; 11 - ZhChKh; 12 - ZhChS; 13 - ZhChSSh; 14 - ZhChYu; 15 - ZhChYuSh; 16 - up to.

Fig. 54 depicts the relative intensity of oxidation at 900° of chromium cast irons with lamellar and spheroidal graphite. The influence of the shape of the graphite inclusions on the scale resistance of silicon cast irons is illustrated in Figures 55 and 56, from which it is to be seen that with graphite of spheroidal shape far higher resistivity to oxidation is ensured than with lamellar graphite. The mechanical properties of cast irons, particularly their toughness and plasticity, also depend on the shape, sizes, and situation of the graphite. These properties are considerably higher in cast irons with graphite of spheroidal shape (or when annealing graphite is formed).

The influence of the shape of the graphite inclusions is clearly shown by comparison of the properties of oxidation-resistant silicon cast iron of brand ZhChS-5.5 of the ordinary type and that modified by magnesium (ZhChSSh-5.5). Cast iron ZhChS-5.5 is characterized by relatively low mechanical properties; its ultimate strength at 20° is 10 kG/mm^2, while at 800° the ultimate strength drops to 2 kG/mm^2. Cast iron ZhChS-5.5 is oxidation-resistant up to 800°; its oxidation resistance drops sharply above 800°.

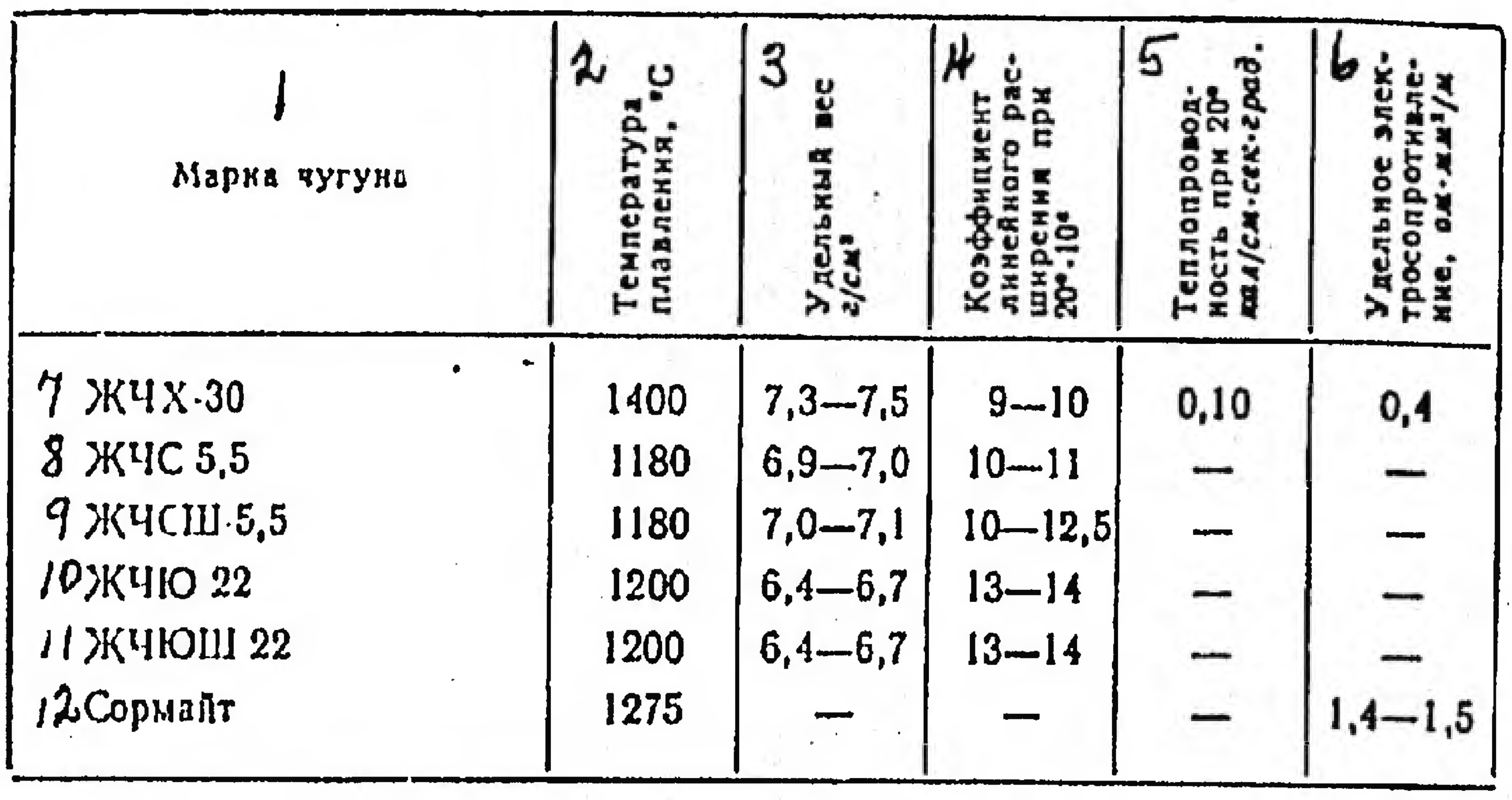
Table 44

Structure Of Oxidation-Resistant Cast Irons [22,44,55]

Brand of Cast Iron	Structure	Brand of Cast iron	Structure
ZhChKh-0.8	Pearlite and cementite	ZhChSSh-5.5	Ferrite and spheroidal graphite
ZhChKh-1.5	Pearlite and cementite	ZhChYu-22	Ferrite, lamellar graphite, and $FeAl_3$
ZhChKh-2.5	Pearlite and cementite	ZhChYuSh-22	Ferrite, spheroidal graphite, and $FeAl_3$
ZhChKh-30	Carbides (iron-chromium), carbide eutectic, and ferrite (alloyed with chromium)	Nicrosilal	Austenite and lamellar graphite
ZhChS-5.5	Ferrite and lamellar graphite	Sormite	Complex carbides, carbide eutectic, and ferrite (alloyed with chromium, nickel, manganese, and silicon)

Table 45

Physical Properties Of Oxidation-Resistant Cast Irons [23, 44]



1 Марка чугуна	2 Температура плавления, °С	3 Удельный вес г/см³	4 Коэффициент линейного расширения при 20°·10⁶	5 Теплопроводность при 20° кал/см·сек·град.	6 Удельное электросопротивление, ом·мм²/м
7 ЖЧХ-30	1400	7,3—7,5	9—10	0,10	0,4
8 ЖЧС 5,5	1180	6,9—7,0	10—11	—	—
9 ЖЧСШ-5,5	1180	7,0—7,1	10—12,5	—	—
10 ЖЧЮ 22	1200	6,4—6,7	13—14	—	—
11 ЖЧЮШ 22	1200	6,4—6,7	13—14	—	—
12 Сормайт	1275	—	—	—	1,4—1,5

1 - brand of cast iron; 2 - melting point, °C; 3 - specific gravity, g/cm^3; 4 - linear expansion coefficient at 20° • 10^6; 5 - thermal conductivity at 20°, cal/cm • sec • degree;; 6 - specific electrical resistance, ohm • mm^2/m; 7 - ZhChKh-30; 8 - ZhChS-5.5; 9 - ZhChSSh-5.5; 10 - ZhChYu-22; 11 - ZhChYuSh-22; 12 - sormite.

Table 46

Mechanical Properties Of Oxidation-Resistant Cast Irons (GOST 7769-63) [23, 55]

1 Марка чугуна	2 Предел прочности при изгибе $\sigma_и$, кГ/мм²	3 Стрела прогиба, мм (расстояние между опорами 300 мм)	4 Предел прочности при растяжении $\sigma_в$, кГ/мм²	5 Твердость по Бринелю НВ
6 ЖЧХ-0,8	36	2,5	18	207—286
7 ЖЧХ-1,5	32	2,5	15	207—286
8 ЖЧХ-2,5	32	2,0	15 Не определяется	228—364
9 ЖЧХ-30	50	2,0	30	370—550
10 ЖЧС-5,5	24	2,0	10	140—255
11 ЖЧСШ-5,5	15 Не определяется	15 Не определяется	22	228—321
12 ЖЧЮ-22	22	2	9	140—286
13 ЖЧЮШ-22	35	2	25	241—375
14 Сормайт	70	—	35—40	460—490

1 - Brand of cast iron; 2 - ultimate bending strength, σ_b, kG/mm²; 3 - bending deflection, mm (distance between supports); 4 - ultimate tensile strength, σ_v, kG/mm²; 5 - brinell hardness, HB; 6 - ZhChKh-0.8; 7 --ZhChKh-1.5; 8 - ZhChKh-2.5; 9 - ZhChKh-30; 10 - ZhChS-5.5; 11 - ZhChSSh-5.5; 12 - ZhChYu-22; 13 - ZhChYuSh-22; 14 sormite; 15 - not determined.

Table 47

Comparative (Tentative) Indices Of Oxidation Resistance Of Cast Irons Tested In Air For 150 Hours At Various Temperatures (Supplement To GOST 7769-63)

1 Температура, °C	2 Марка чугуна							
	3 ЖЧХ-0,8	4 ЖЧХ-1,5	5 ЖЧХ-2,5	6 ЖЧХ-30	7 ЖЧС-5,5	8 ЖЧСШ-5,5	9 ЖЧЮ-22	10 ЖЧЮШ-22
	11 Величина окалинообразования, г/м²·ч							
500	0,20	0,20	0,15	—	—	—	—	—
600	0,50	0,50	0,50	—	—	—	—	—
700	0,50	0,50	0,50	—	—	—	—	—
800	3,50	1,50	1,50	—	0,20	0,05	—	—
900	15,00	15,00	15,00	0,2	10,0	0,20	—	—
1000	—	—	—	0,2	20,0	1,00	0,05	—
1100	—	—	—	—	—	—	0,10	0,05
	12 Величина роста, %							
500	0,05	—	—	—	—	—	—	—
600	0,20	0,05	—	—	—	—	—	—
700	0,30	0,20	0,10	—	—	—	—	—
800	0,50	0,50	0,50	—	0,40	—	—	—
900	1,50	1,00	0 75	—	0,50	0,20	—	—
1000	—	—	—	—	1,00	0,70	—	—
1100	—	—	—	—	—	—	0,05	—

Translation of items in Table 47: 1 - temperature, °C; 2 - brand of cast iron; 3 - ZhChKh-0.8; 4 - ZhChKh-1.5; 5 - ZhChKh-2.5; 6 - ZhChKh-30; 7 - ZhChS-5.5; 8 - ZhChSSh-5.5; 9 - ZhChYu-22; 10 - ZhChYuSh-22; 11 - amount of scale formation, $g/m^2 \cdot h$; 12 - amount of growth, %.

When cast iron is modified by magnesium in the amount of up to 0.1%, it acquires a different structure, that is, the graphite assumes a spheroidal shape. As a result there is a sharp change in its properties; in particular, the scale resistance increases at up to 900°. ZhChSSh-5.5, which is modified by magnesium, is the most highly oxidation-resistant of the silicon cast irons. Silicon cast iron with spheroidal graphite has at room temperature and at 800° a strength which is twice as great as that of the same cast iron with lamellar graphite. A distinctive feature of silicon cast iron is its extremely high plasticity at a high (800°) temperature: δ = 30-40%, ψ = 60-70%, while with silicon cast iron with lamellar graphite δ = 1.5%. The hardness of silicon cast iron with spheroidal graphite ZhChSSh-5.5 is higher than that of cast iron of brand ZhChS-5.5

The use of oxidation-resistant cast irons is shown in Table 48.

It is to be seen from the table that the highest strength is possessed by high-chromium cast iron ZhChKh-30.

In addition to high oxidation resistance and growth stability, cast iron ZhChKh-30 is characterized by great high-temperature strength; its dimensions undergo virtually no change in protracted and cyclic heating.

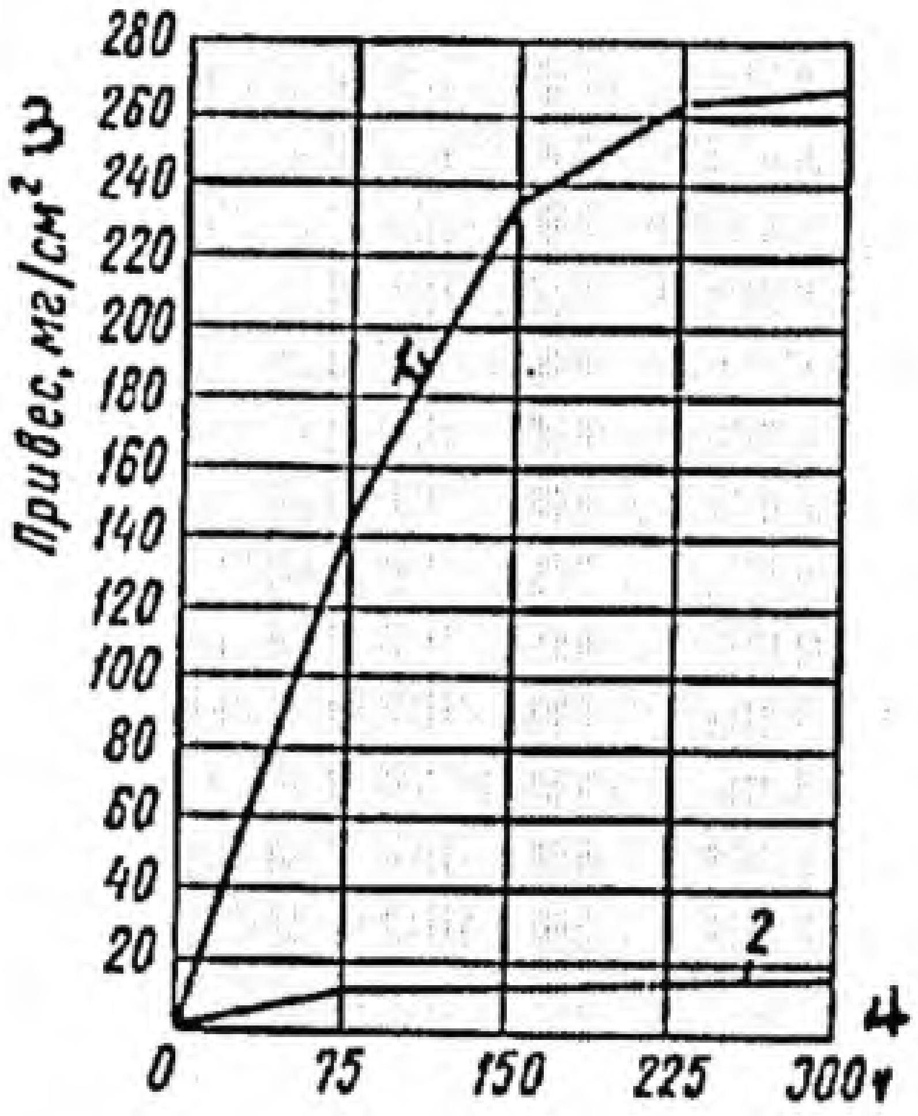


Fig. 54. Intensity of oxidation of chromium cast irons with lamellar and spheroidal graphite at a temperature of 900° (Mil'man):

1 - cast iron with lamellar graphite;
2 - cast iron with spheroidal graphite;
3 - weight gain, mg/cm^2;
4 - hours.

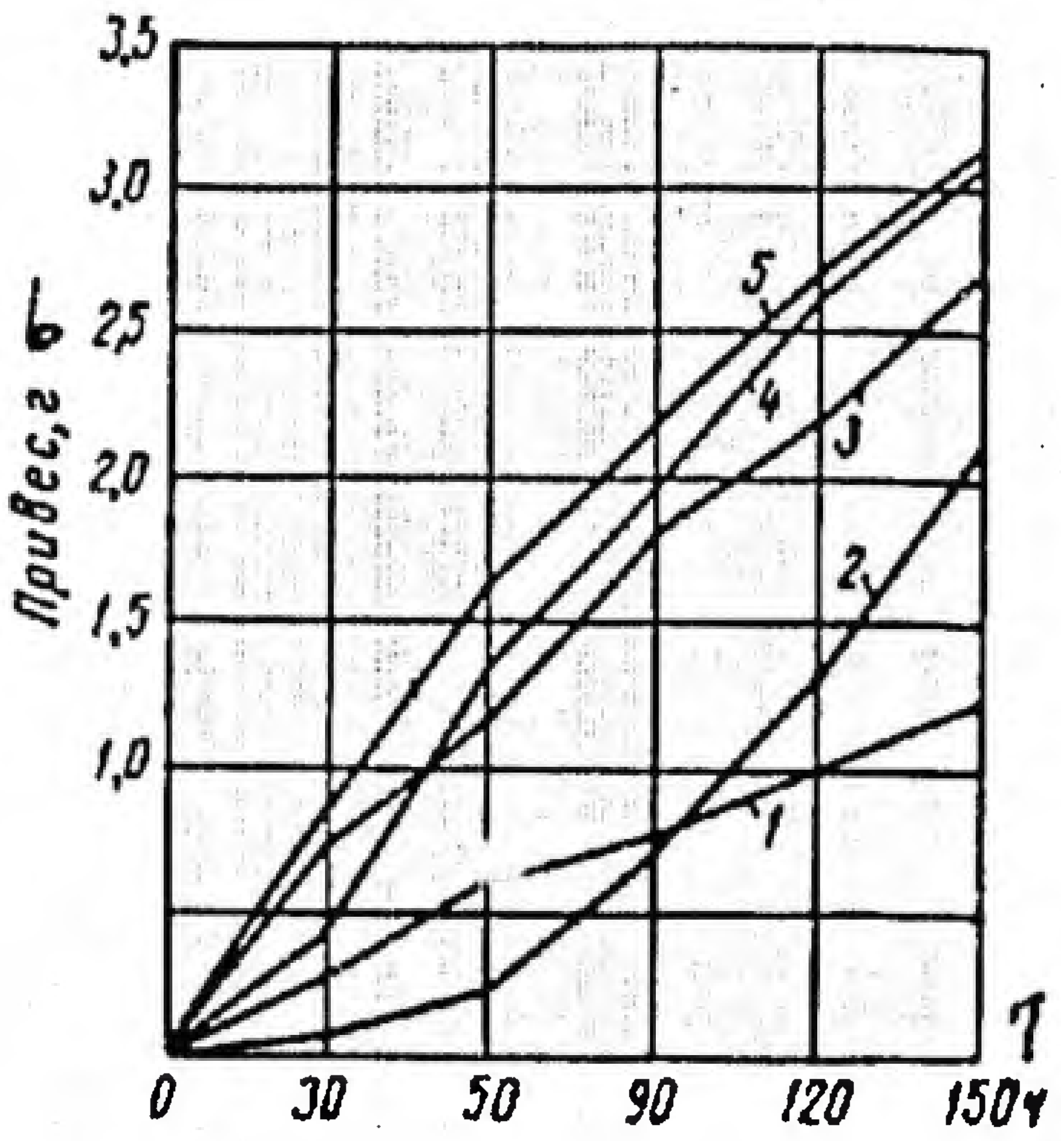


Fig. 55. Scale resistance of silicon cast iron with lamellar graphite at 1000° [44]:

1 - Si = 6.26%; Mn = 3.83%;
2 - Si = 5.62%; Cr = 1.26%;
3 - Si = 5.02%; Cr = 0.86%;
4 - Si = 5.4%;
5 - Si = 5.94%
6 - weight gain, g;
7 - hours.

Table 48

Use Of Oxidation-Resistant Cast Irons (GOST 7769-63) [23, 55]

Brand of cast iron	Operating temperature	Basic purpose
ZhChKh-0.8	Up to 550° in an atmosphere of air and furnace gases	Gate valves of gas generators, grate bars, chill boxes of open-hearth furnaces, and other parts
ZhChKh-1.5	Up to 600° in an atmosphere of air, furnace gases, or generator gases	Grate bars, grate holders, rabbles, and teeth of pyrite furnaces, chill boxes for open-hearth furnaces, spacer crests of steam boilers, recovery pipes, and other parts
ZhChKh-2.5	Up to 650° in an atmosphere of air, furnace, or generator gases	
ZhChKh-30	Up to 1000° in an atmosphere of air and furnace gases	Parts of centrifugal pumps, reactors, condensers, pipes, fractionating columns, fans, mixers, miscellaneous equipment; parts subjected to wear at high temperatures - furnace conveyor chains, hearthglobes. Parts of fire boxes, drum dryers, blades, rabbles of pyrite furnaces, retorts, smelting pots Parts of chemical equipment
ZhChS-5.5	Up to 800° in an atmosphere of air, furnace gases, or generator gases	Recovery pipes, throttle valves, chill boxes for open-hearth furnaces, reflecting plates of coal burners, grate beams for steam boilers, etc.
ZhChSSh-5.5	Up to 900° in an atmosphere of air and furnace gases	Recovery pipes, grate bars, etc.
ZhChYu-22	Up to 1000° in an atmosphere of air and furnace gases	For castings subjected to high temperatures: thermocouple covers, furnace fittings, teeth of pyrite furnaces, gratings, vessels for melted non-ferrous metals, fused salts, etc.
ZhChYuSh--22	Up to 1100° in an atmosphere of air and furnace gases	
Nicrosilal	Up to 1100° in an atmosphere of air and furnace gases	Melting pots, retorts, connecting pieces, grate bars and other parts of burners, carburizing containers; cast heaters
Sormite	Up to 850° in an atmosphere of air	For cast heaters of electric furnaces, for wear-resistant and oxidation-resistant deposits

Cast iron of the nicrosilal brand is one of the oxidation-resistant austenitic cast irons. In oxidation resistance it is not inferior to cast irons high-alloyed with aluminum.

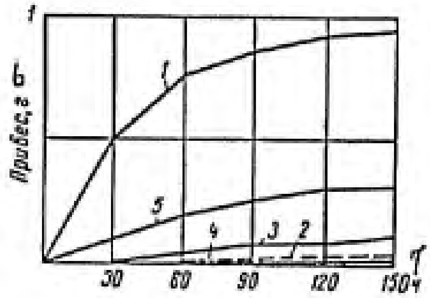


Fig. 56. Scale resistance of silicon cast iron with spheroidal graphite at 1000° [44]:
1 - Si = 4.59%, Mn = 3.08%;
2 - Si = 5.79%, Cr = 1.43%;
3 - Si = 5.03%, Cr = 0.63%;
4 - Si = 5.85%
5 --Si = 5.6%, Mn = 2.75%;
6 - weight gain, g;
7 - hours.

Aluminum cast irons of brands ZhChYu-22 and ZhChYuSh-22 containing up to 25% aluminum have been employed of late in industry.

While having a relatively high hardness ensuring good machinability, cast iron ZhChYuSh-22 with spheroidal graphite retains adequate strength at a high temperature (14 kG/mm^2 at 800°). The presence of the phase $FeAl_3$ in aluminum cast irons imparts considerable brittleness to them.

The use of aluminum cast iron of brand ZhChYuSh-22 for casting the teeth of pyrite furnaces has lengthened the service life of the teeth fifteen-fold in comparison with those of unalloyed gray cast iron.

B. NON METALLIC-MATERIALS

Metal ceramics stable at high temperatures and thermostable plastics have come to be widely used of late in industry along with oxidation-resistant metals and alloys.

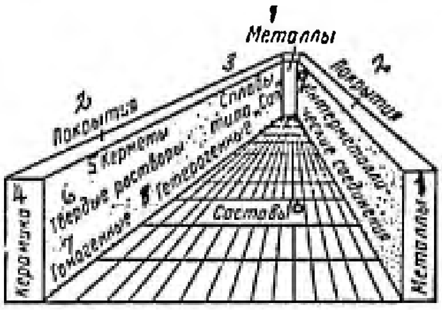


Fig. 57. Diagram of conventional classification of oxidation-resistant materials (Schwarz); 1 - metals; 2 - coatings; 3 - alloys of the "SAP' type; 4 - ceramics; 5 - cermets; 6 - solid solutions; 7 - homogeneous; 8 - heterogeneous; 9 -- intermetallic compounds; 10 - compositions.

A conventional classification of oxidation-resistant materials is shown in the diagram in Fig. 57. Included in this classification are high-temperature materials from pure ceramics (left--hand portion of diagram) to metals (right-hand portion of diagram). The intermediate groups represent a mixture of ceramics and metals or intermetallic compounds. Also indicated here are coatings consisting of ceramics and cermets, as well as metallic coatings.

A description of metal-ceramic and plastic materials is given below.

B. NON-METALLIC MATERIALS

5. METAL-CERAMIC MATERIALS

Metal-ceramic materials, or so-called cermets, represent a composition of refractory ceramic compounds (oxides, carbides, nitrides, borides, silicides) and metallic binders. Cobalt, nickel, molybdenum, chromium, tungsten, beryllium, and other metals may be employed as the metallic binder.

Certain physical and mechanical characteristics of refractory metals and their ceramic compounds entering into the composition of metal-ceramic materials are shown in Table 49.

The distinctive properties of ceramic compounds -- carbides, nitrides, silicides, and borides -- are refractoriness, hardness, and brittleness. The high moduli of elasticity of these compounds attest to the strong interatomic bond.

The carbides and borides of refractory metals contain from 6 to 31% carbon or boron; the nitrides contain from 3 to 22% (by weight) of nitrogen; and the silicides from 23 to 54% (by weight) of silicon. However, despite the high content of non-metals, these compounds possess pronounced metallic properties [63].

Table 50 shows the stability of refractory compounds toward oxidation in air. It is to be seen that the silicides of molybdenum and tungsten, the nitrides of silicon, the borides of chromium and titanium, and the carbides of chromium, titanium, and zirconium are characterized by the highest scale resistance. The carbides of molybdenum and tungsten are characterized by low scale resistance, this being partly explained by the high volatility of the oxides of these metals, which fosters loosening of the oxide layer.

The process of producing metal-ceramic articles consists in the sintering of chemically pure, prepressed finefrain (no larger than 10 μ) powders of metal and ceramics at high temperatures and under high pressures. The sintering temperature of ceramic articles is regulated by the melting point of the metallic bond. At the same time, it is advisable to bring the metallic bond to fusion whenever particles of the ceramics are wetted by the liquid metal. The pressure in the sintering of metal-ceramic powders is 30-140 kG/cm^2 [76]. Sintering of the powders is carried out in a reducing or neutral atmosphere (hydrogen, argon, or nitrogen).

Three forms of cermets are distinguished, in keeping with the nature of the bond between the ceramic and the metallic particles [13].

1. Mechanical mixtures. Their components do not enter into reactions. The bond between the particles is assured through mechanical adhesion of the ceramics with the surrounding metal. This group of cermets includes Ni-BeO, Mo-Al_2O_3, Mo-ThO, and others.

2. On sintering the components form spinels, that is, complex oxides, at the points of contact between the metal and the ceramics. Cermets of this type are formed at higher temperatures than are mechanical mixtures. Cr-Al_2O_3 and others are to be cited as an example of this group of cermets.

3. Cermets which form solid solutions or chemical compounds in the sintering process: TiC-Co, TiC-Ni, Be-MgO, $Zr\text{-}Al_2O_3$, and others.

Cermets

Cermets based on oxides are characterized by refractoriness, high resistivity to oxidation, and high mechanical strength up to 1200° and above, but they do not resist mechanical impacts well. For instance, the cermets containing aluminum oxide,

LT-1 .... 77% Cr, 23% Al_2O_3;

LT-iv............... 60% Cr, 18% Al_2O_3, 20% Mo, 2% TiO_2;

LT-2................ 25% Cr, 15% Al_2O_3, 60% W,

along with high resistivity to oxidation, wear, and high-temperature erosion, preserve adequate strength at temperatures above 1260° and lend themselves well to machining by turning and grinding. However, these cermets are characterized by relatively high brittleness, for which reason they may be employed only in unstressed structures which are not subjected to mechanical impacts.

Cermets of this type are subjected to particularly heavy embrittlement in a carburizing atmosphere at high temperature. The cermets in question cannot be recommended for operation in contact with fused aluminum.

The cermets based on the borides of refractory metals are characterized by similar properties. They are refractory, have a high hardness, resist oxidation and thermal shocks well, and preserve a high strength up to 1100°, but resist mechanical impacts poorly.

In practice use is made as oxidation-resistant materials of complex borides or alloys of borides and silicon or silicides of metals on which there is formed on heating, an oxide film consisting predominantly of boron-silicate glass and protecting the alloy well against oxidation.

The boride alloys are characterized by high stability toward the action of fused metals, especially ones such as aluminum, copper, tin, etc., as well as fluorine compounds [56]. Owing to this feature, the alloys of borides are utilized as a material for the heaters of electric furnaces, for the lining of metallurgical and glass furnaces, and also as the protective covers of immersion thermocouples.

The borides are also characterized by chemical stability at normal and high temperatures, this permitting their use in manufacture of parts of chemical apparatus subjected to the action of high temperatures accompanied by the action of pulps or aerosols.

Table 49

Certain Physical And Mechanical Characteristics Of Refractory Metals And Their Ceramic Compounds 52, 63

1 Металл, соединение	2 Удельный вес, г/см³	3 Температура плавления, °С	4 Теплопроводность при 20—100° кал/см·сек·°С	5 Коэффициент линейного расширения при 20—100° $\times 10^6$	6 Удельное электросопротивление, ом·мм²/м	7 Теплоемкость кал·г/град	8 Коэффициент Пуассона	9 Предел прочности $\sigma_в$ кГ/мм²		12 Модуль упругости кГ/мм²		15 Микротвердость кГ/мм²
								10 при сжатии	11 при изгибе	13 при растяжении	14 при сдвиге	
Ti	4,5	1725	0,11	8,5	0,55	0,140	0,36	—	—	10 520	3 870	157
TiC	4,93	3140	0,058	7,42	0,52	0,229	0,41	138	87	32 000	11 364	3000
TiN	5,2	2950	0,048	9,35	0,25	0,193	0,45	130	—	25 600	8 821	2160
TiB_2	4,45	2000	0,058	6,39	0,144	0,154	0,42	135	—	37 400	13 187	3370
$TiSi_2$	4,35	1460	—	—	0,169	0,145	—	—	21	26 400	—	870
Zr	6,5	1860	—	8,9	0,41	0,060	0,37	—	—	6 970	2 540	97
ZrC	6,9	3530	0,049	6,74	0,50	0,080	0,43	—	—	35 500	12 369	2925
ZrN	6,97	2980	0,040	10,1	0,211	0,111	—	100	—	—	—	1988
ZrB_2	5,8	3040	0,058	6,83	0,166	0,120	0,42	159	—	35 000	12 324	2252
$ZrSi_2$	4,88	1700	—	—	0,758	0,095	—	—	—	26 800	—	1030
V	6,0	1720	0,070	9,7	0,26	0,120	0,35	—	—	15 000	5 500	65
VC	5,36	2830	0,059	7,2	0,65	0,162	0,45	62	—	27 600	9 530	2094
VN	6.04	2360	0,042	8,35	0,85	0,178	—	—	—	—	—	1520
VB_2	4.6	2400	—	—	0,19	0,160	—	—	—	—	—	2044
VSi_2	4,42	1750	—	—	0,665	0,130	—	—	—	—	—	1090
Nb	8,5	2415	—	7,1	0,131	0,065	0,35	—	—	16 000	6 000	—
NbC	7,56	3500	0,034	6,5	0,511	0,078	0,44	—	—	34 500	11 946	1961
Nb_2C	—	—	—	—	—	—	—	—	—	—	—	2123
NbN	8,4	2300	0,008	10,1	0,60	0,097	—	—	—	—	—	1400
NbB_2	7.0	3000	0,040	7,9—8,3	0,34	0,100	—	—	—	—	—	2600
$NbSi_2$	5,45	1950	—	—	0,504	0,094	—	—	—	—	—	1050
Ta	16,6	2850	0,13	6,5	0,124	0,036	0,35	—	—	18 820	7 000	108
TaC	14,3	3880	0,053	8,2	0,421	0,042	0,45	—	—	29 100	10 358	1599
TaN	13,8	3090	—	—	2,00	0,067	—	—	—	—	—	1060
Ta_2C	—	3400	—	—	—	—	—	—	—	—	—	1714
TaB_2	11,70	3100	0,026	5,12	0,374	0,580	—	—	—	26 200	—	2500
$TaSi_2$	8,83	2200	—	—	0,461	0,059	—	—	—	—	—	1560
Mo	10,2	16 2620	0,35	6,0	0,05	0,060	0,31	—	—	33 630	12 200	192
Mo_2N	8,0	Разлагается	—	—	—	0,044	—	—	—	—	—	—
Mo_2C	9,18	2690	0,016	4,4	0,71	0,072	0,34	—	—	54 400	20 268	1499
Mo_2B	9,1	2142	—	—	0,40	—	—	—	—	—	—	1790
$MoSi_2$	6,3	2030	0,7	5,1	0,25	0,092	—	113	25—40	43 000	—	1230
W	19,3	3400	0,47	4,4	0,05	0,032	0,3	—	—	51 520	15 140	350
WC	15,55	2600	0,07	3,9	0,192	0,044	0,37	360	35	61 300	22 405	1780
WN	12,1	17 Разлагается при 600°	—	—	—	0,049	—	—	—	—	—	—
W_2C	—	2700	0,07	5,5	—	—	0,38	—	—	42 800	15 484	3000
W_2B	10,0	2770	—	—	—	—	—	—	—	—	—	2350
WSi_2	9,33	2165	—	—	0,125	0,058	—	—	—	—	—	1090
CrB_2	5,6	2200	0,076	11,1	0,56	0,112	—	128	62	21 500	—	1800
$CrSi_2$	4,4	1500	0,015	—	9,2	0,157	—	—	—	—	—	1150
Cr_3C_2	6,68	1895	0,046	11,7	0,75	0,129	—	—	—	38 000	—	1360
Cr	7,2	1860	0,160	6,2	0,189	0,106	—	—	—	—	—	—
CrN	6,2	18 Разлагается при 1500°	0,030	—	6,1	0,15	—	—	—	—	—	1080

Translation of Table 49: 1 - metal, compound; 2 - specific gravity, g/cm^3; 3 - melting point, °C; 4 - thermal conductivity at 20-180°, cal/cm · sec · °C; 5 - linear expansion coefficient at 20-100° X 10^6; 6 - specific electrical resistance, ρ, ohm · mm^2/m; 7 - heat capacity, cal · g/degree; 8 - Poisson ratio; 9 - ultimate strength, σ_b, kG/mm^2; 10 - compressive; 11 - transverse; 12 - modulus of elasticity, kG/mm^2; 13 - in tension; 14 - in shear; 15 - microhardness, kG/mm^2; 16 - decomposes; 17 - decomposes at 600°; 18 - decomposes at 1500°.

Table 50

Stability Of Refractory Compounds Toward Oxidation In Air [63]

1 Металл	2 Температура интенсивного окисления, °C			
	3 Карбид	4 Нитрид	5 Борид	6 Силицид
7 Титан	1000—1200	1000—1200	1100—1300	900—1100
8 Цирконий	1100—1200	1000—1200	1000—1100	900—1100
9 Ванадий	800—900	500—800	800—900	800—1000
10 Ниобий	900—1000	500—800	800—900	800—1000
11 Тантал	900—1000	500—800	800—900	900—1100
12 Хром	1100—1200	—	1200—1300	1000—1200
13 Молибден	500—800	—	1000—1100	1650—1700
14 Бор	800—1000	900—1000	—	1000—1200
15 Вольфрам	500—800	—	1000—1100	1500—1600

1 - metal; 2 - temperature of intensive oxidation, °C; 3 - carbide; 4 - nitride; 5 - boride; 6 - silicide; 7 - titanium; 8 - zirconium; 9 - vanadium; 10 - niobium; 11 - tantalum; 12 - chromium; 13 - molybdenum; 14 - boron; 15 - tungsten.

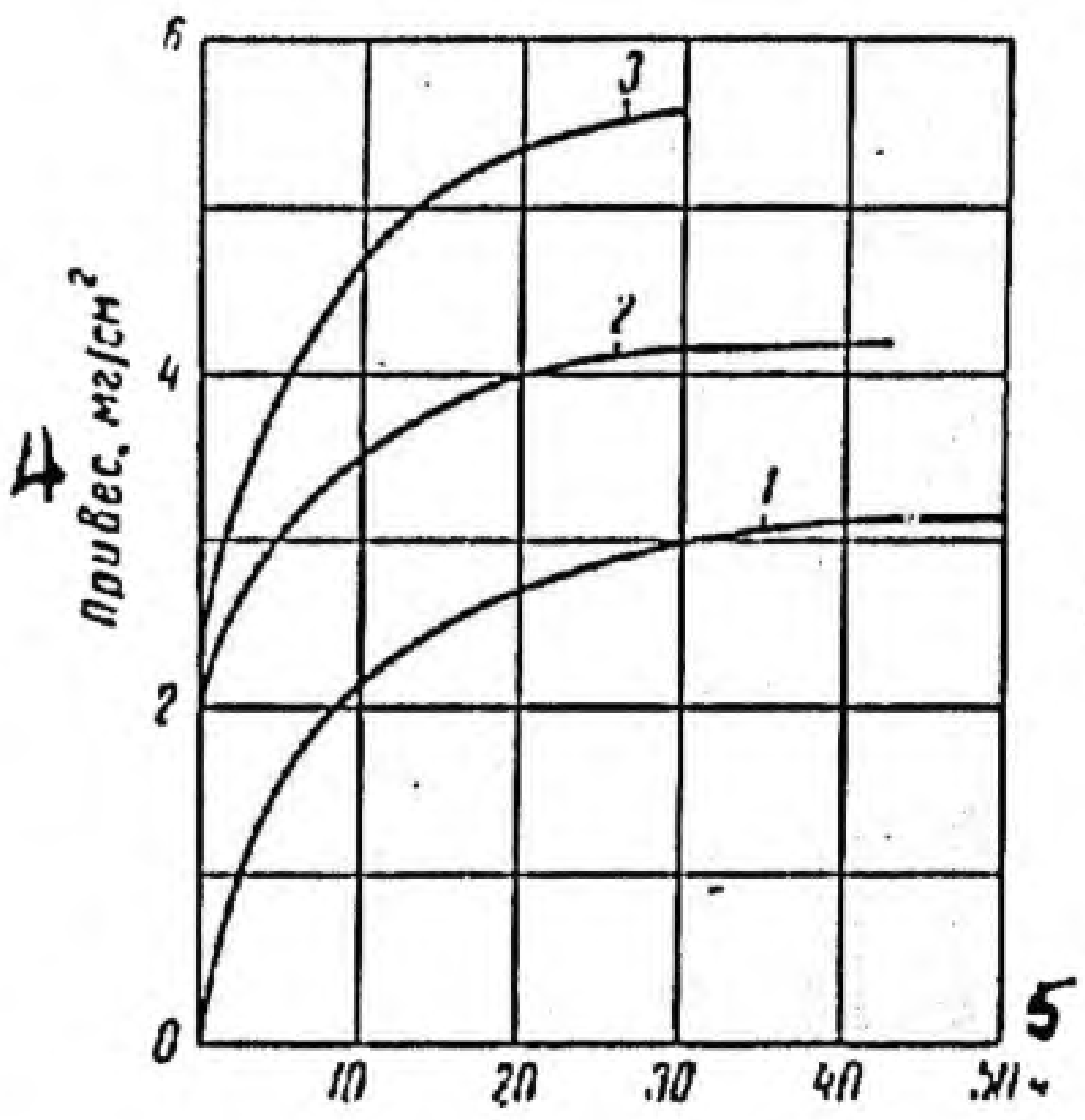


Fig. 58. Kinetics of oxidation of metal-ceramic alloy WZ-12b [13]:

1 - at 900°;
2 - at 1000°;
3 - at 1100°;
4 - weight gain, mg/cm^2;
5 - hours.

The high chemical stability of the boride alloys, combined with their oxidation and wear resistance, opens up prospects for their future use in the production of the arcing tips of electrical circuit breakers.

Metal-ceramic materials based on carbides, chiefly the carbides of titanium and tungsten, have been p , to the widest use.

The quantity of carbides in hard alloys comprises 95-85%, the balance being the binding metal. Carbides impart high hardness and wear resistance to an alloy. However, the carbides are in themselves very brittle, so that the binding metal performs the function of a cement: in binding the carbide particles it imparts the necessary strength and toughness to the entire alloy.

Use is made as a binding metal chiefly of cobalt and nickel, which do not form carbides of their own and ensure high mechanical properties for an alloy.

Among the metal-ceramic alloys based on carbides, tungsten--cobalt and titanium-tungsten-cobalt alloys have come to be the most widely used ones in the Soviet Union. These alloys are characterized by high hardness and wear resistance and are employed primarily for the surfacing of cutting tools.

Metal-ceramic solid alloys based on titanium carbide combine high scale resistance and high-temperature strength, while preserving their toughness properties. Owing to this fact, alloys of the type in question are employed in gas turbine construction and other branches of industry. Certain of these alloys adopted abroad are given in Table 51.

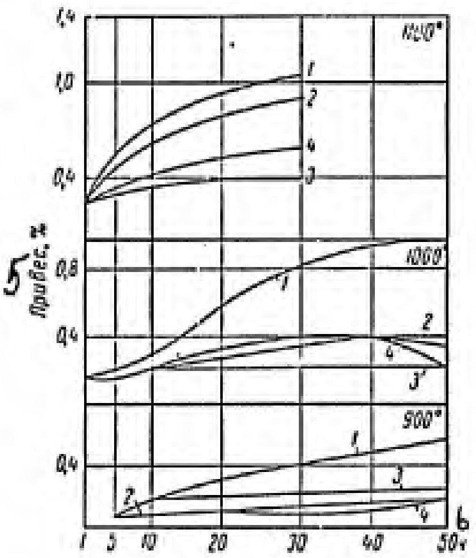


Fig. 59. Kinetics of oxidation of metal-ceramic alloys based on titanium carbide 92 :

1 - alloy WZ-2;
2 - alloy WZ-3;
3 - alloy WZ-12;
4 - alloy WZ-5;
5 - weight gain, %;
6 - hours.

Фиг. 59. Кинетика окисления металло-керамических сплавов на основе карбида титана [92]: 1 — сплав WZ-2; 2 — сплав WZ-3; 3 — сплав WZ-12; 4 — сплав WZ-5.

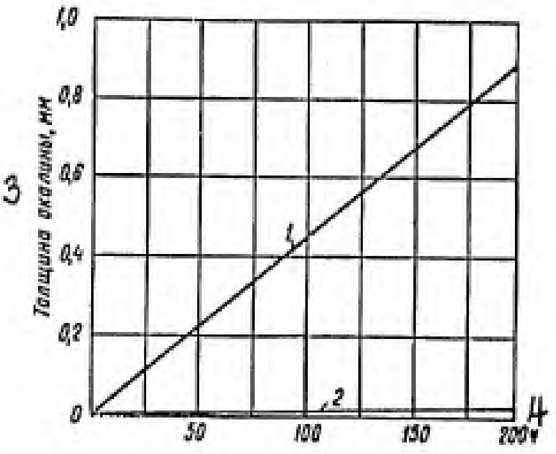


Fig. 60. Kinetics of oxidation of metal-ceramic alloys based on titanium carbide 31 :

1 - 80% TiC and 20% Co;
2 - 63.3% TiC, 18.7% Co, and 15% (NbC TaC TiC);
3 - scale thickness, mm;
4 - hours.

The kinetics of oxidation of metal-ceramic alloys based on titanium carbide is shown in Figures 58-60.

Titanium carbide is characterized by high refractoriness: its melting point is higher than 3100°; it resists oxidation well. The favorable influence of titanium carbide on the scale resistance of alloys is explained by the formation on their surface of a strong gas-impervious oxide film of TiO. The titanium oxides are stable toward the action of fused metals. Articles of titanium carbide are not wetted and virtually do not interact with fused tin, lead, bismuth, cadmium, zinc, and aluminum. Titanium carbide is not wetted by fused copper in a vacuum at temperatures of 1100-1300°, or by silver at 980° in a vacuum. Iron, cobalt, and nickel become well wetted and erode titanium carbide. The addition to solid alloys based on titanium carbide of other carbides such as the carbides of niobium, tantalum or tungsten contribute to increase in the scale resistance of the alloys.

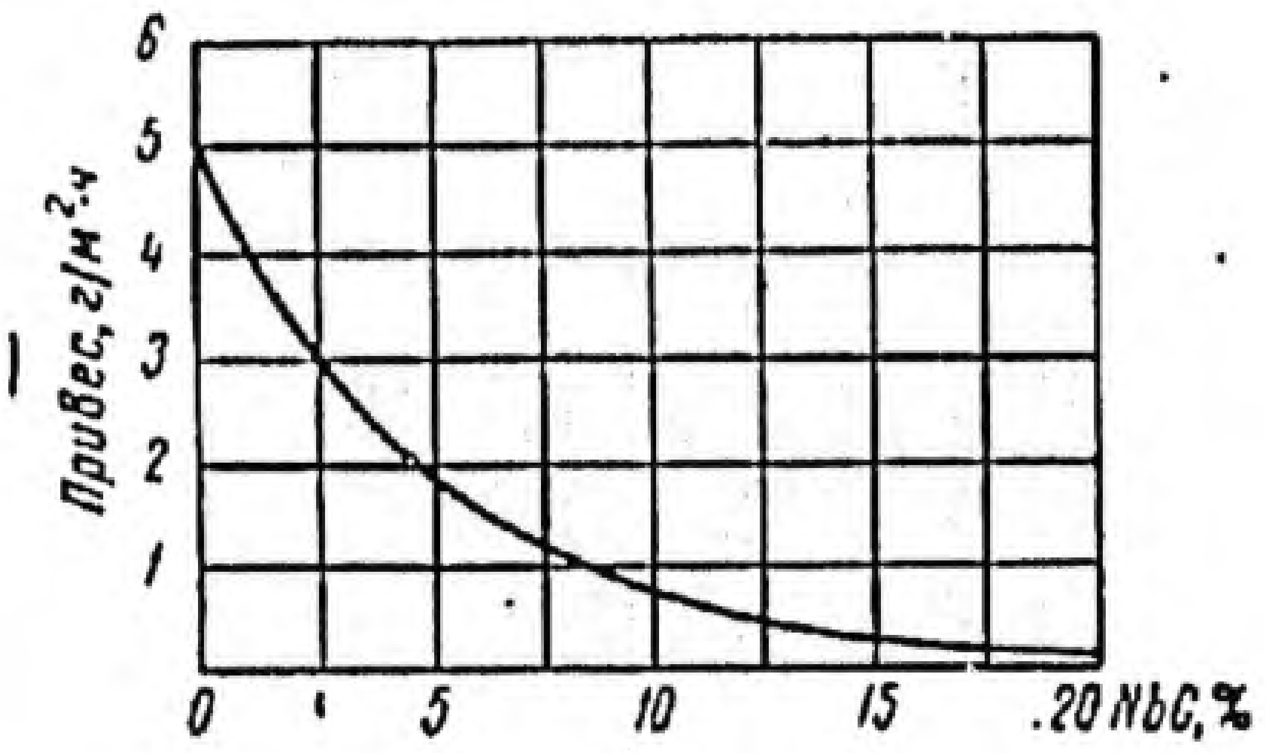


Fig. 61. The influence of niobium carbide on the scale resistance of a metal-ceramic alloy based on titanium carbide at 1100° (Brokhin and Ol'khov):

1 - weight gain, g/m^2 · h.

The influence of niobium carbide on the scale resistance of an alloy based on titanium carbide is illustrated in Fig. 61, from which it is to be seen that in TiC-NbC-Co alloys containing 50-75% TiC and 15-25% Co, increase in the NbC content to 12-15% leads to considerable increase in the scale resistance of the alloy. The addition of more than 10% niobium carbide ensures the formation of a tight and strong layer of oxides. The optimum alloy is that containing 15% NbC, 25% Co, and a balance of TiC. Such an alloy possesses satisfactory scale resistance up to 1100°.

Among the carbide-titanium-cobalt alloys having an admixture of tungsten carbide, the best one is the alloy containing 30% WC, 15-20% Co, and a balance of TiC. The scale resistance of this alloy is satisfactory up to 900°.

To increase the resistivity to oxidation of alloys based on titanium carbide (TiC-Co, TiC-Ni), solid solutions of the carbides of niobium, tantalum, and titanium are also added to them. The influence of a solid solution of NbC-TaC-TiC on the scale resistance of solid alloy TiC-Co is shown in Figure 62.

The most favorable influence on the scale resistance of the alloy TiC-Co is manifested when the latter contains a solid solution of the carbides NbC-TaC-TiC in the amount of 10-12%; the scale resistance is impaired by a higher amount.

A considerable influence on increase in the resistivity of cermets to oxidation is exerted by the metallic binder. Such binding metals as cobalt and nickel increase the oxidation resistance of alloys based on titanium carbides up to 1100-1150° [13].

Table 51

Composition And Properties Of Metal-Ceramic Solid Alloys Employed In Foreign Countries 13, 31, 68

1 Марка кермета	2 Химический состав, % (весовые) Ti+C	TaC	Ni	Co	Cr	Mo	5 Процент связи (приблизительно)	6 Удельный вес, г/см³	3 Окисляемость, (мг/см²) при 1000° в течение 7 100 ч	7 200 ч	4 Механические свойства 8 Прочность на изгиб $\sigma_и$, кГ/мм²	9 Относительное удлинение δ после 100 ч работы при 1000°, %	10 Твердость по Роквеллу HRA	11 Модуль упругости кГ/мм²	12 Длительная прочность в течение 100 ч при 1000°, кГ/мм²
FS-2	60,6	—	29,6	—	7,4	1,4	34,2	6,0	9,0	15,6	122,5	9	87	—	9,8
FS-8	61,6	—	22,2	7,4	7,4	1,4	34,2	6,06	11,0	22,9	122,5	7	87	—	9,1
FS-9	48,6	—	30,0	10,0	10,0	1,4	47,2	6,47	7,5	12,3	140	10	84	—	8,5
FS-10	33,6	—	52,0	—	13,0	1,4	62,0	6,95	6*	10*	154	10	79	—	6,5
FS-12	33,6	—	39,0	13,0	13,0	1,4	62,0	6,95	6*	10*	154	10	79	—	6,5
FS-26	55,1	—	40,0	—	4,9	—	42,2	6,26	31,5	47,6	126	6	83	—	8,2
FS-27	44,5	—	50,0	—	5,5	—	53,0	6,25	7,6	13,6	136	7	79	—	6,6
FS-65	50,3	—	35,0	—	10,0	4,7	43,7	6,25	6,1	9,5	104	4	87	—	9,5
WZ-2	—	60	—	28	12	—	—	6,0—6,6	13 См. фиг. 59	—	140—147	—	1160HV	—	—
WZ-12	—	62	15	15	10	—	—	6,25	13 См. фиг. 59	—	147—165	—	1340HV	39 500	—
WZ-3	(TiC+TaC+NbC=60)		32	—	8	—	—	6,0—6,6	13 См. фиг. 59	—	147—168	—	1090HV	—	—
WZ-5	—	50	40	—	10	—	—	6,0—6,6	13 См. фиг. 59	—	—	—	830HV	—	—
K-138	—	80	—	20	—	—	—	5,5	0,196 мм	—	123	—	90	38 500	—
K-138A	(TiC+TaC+NbC=80)			20	—	—	—	5,8	0,024 мм	—	105	—	89	40 300	—
K-151A	(TiC+TaC+NbC=80)		20	—	—	—	—	5,8	0,022 мм	—	105	—	89	40 000	—
K-152B	(TiC+TaC+NbC=70)		30	—	—	—	—	6,0	0,139 мм	—	148	—	86	36 000	—
WZ-126	—	60	24	8	8	—	—	6,2	См. фиг. 58	—	—	—	1090HV	—	11

14* Вычислено.

1 - brand of cermet; 2 - chemical composition, % (by weight); 3 - oxidizability (mg/cm²) at 1000° during; 4 - mechanical properties; 5 - percentage of bond (approximate); 6 - specific gravity, g/cm³; 7 - hours; 8 - bending strength, σ_u, kG/mm²; 9 - elongation per unit length, δ, after 100 hours operation at 1000°, %; 10 - Rockwell hardness, HRA; 11 - modulus of elasticity, kg/mm²; 12 - stress-rupture strength during 100 hours at 1000°, kG/mm²; 13 - see Fig. 59; 14 - calculated.

The use of binding alloys such as cobalt-chromium, nickel-chromium-cobalt, nickel-aluminum, and nickel-molybdenum alloys increases even further the oxidation resistance of metal-ceramic alloys based on titanium carbide. Some of these alloys (Table 51) have been employed as scale-resistant alloys.

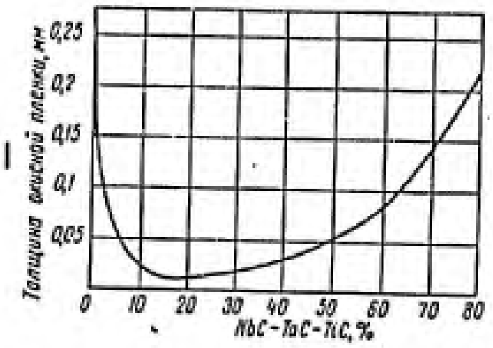


Fig. 62. Influence of a solid solution of carbides NbC-TaC-TiC on the scale resistance of metal-ceramic TiC-Co alloys at 980°; test period 64 hours [13]:

1 - Thickness of oxide film, mm.

A higher resistance to oxidation, in comparison with alloys based on titanium, is possessed by sintered materials, which abroad are termed "turbides", they are produced on the basis of the carbides of chromium Cr_3C_2 and titanium TiC by use of 10 to 60% of binding alloys: Ni-Cr, Co-Cr, or Ni-Cr-Co.

A general disadvantage of metal-ceramic alloys based on oxides, borides, and carbides is their brittleness at room temperature.

Silicides

The silicides of refractory metals have in recent years come to be employed in industry as scale-resistant materials. Molybdenum disilicide, $MoSi_2$, has been the most widely used.

Molybdenum disilicide is produced by heating a mixture of powders of molybdenum and silicon in an atmosphere of inert gas at 900--1100°. Molybdenum disilicide is characterized by high resistivity to oxidation up to 1700° and above. When it is heated there is formed on its surface a tight, nonporous, firmly adhering virtreous film of silicon dioxide which protects it from further oxidation.

The silicon dioxide film forming on the surface of $MoSi_2$ is impervious to oxygen at high temperatures. Herein lies the fundamental difference between the mechanism of oxidation of molybdenum disilicide and certain oxidation-resistant alloys, with which diffusion of oxygen through the oxide film occurs at high temperatures. A peculiarity of the silicon dioxide film is its capacity of self-reduction, this being of particular importance when it is damaged or cracked.

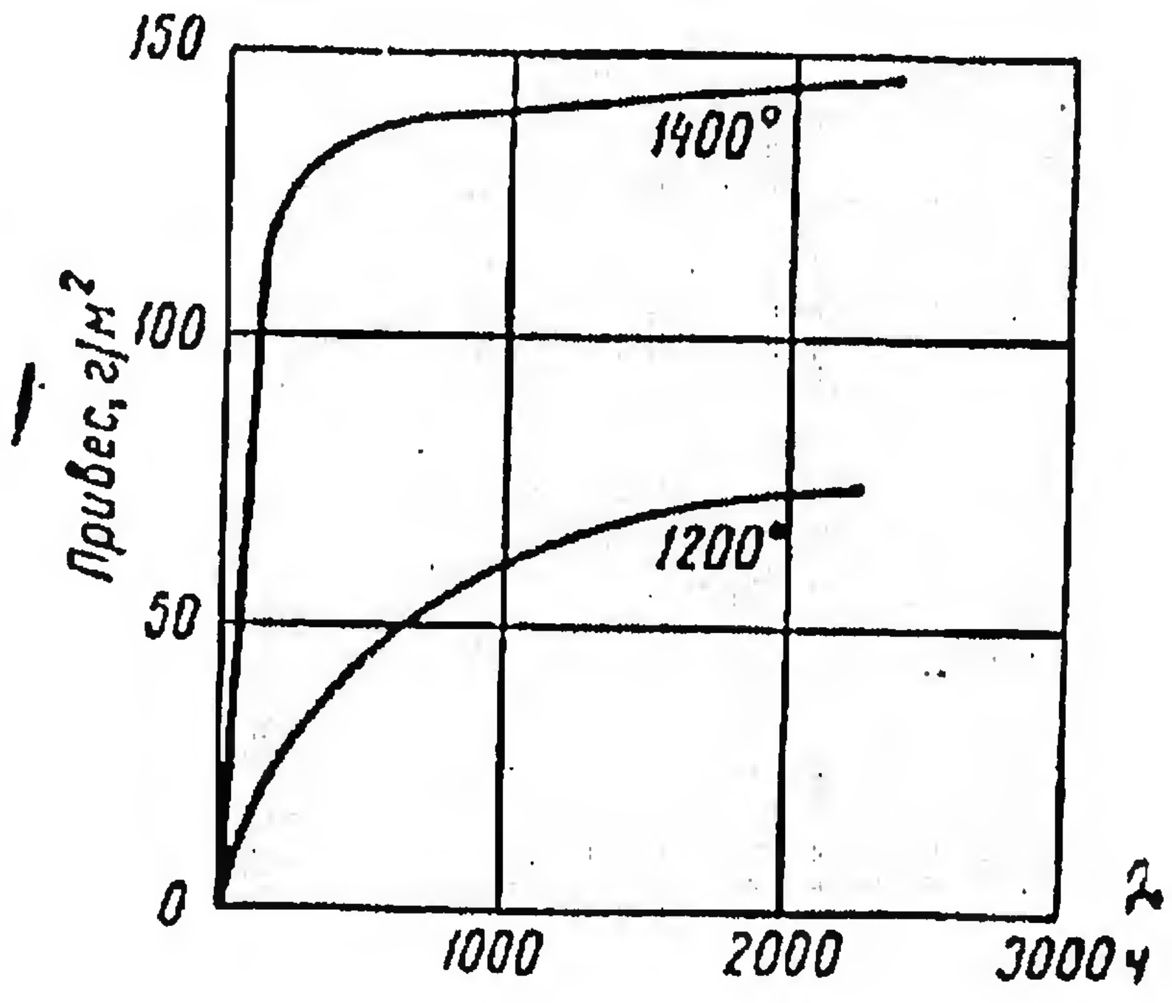


Fig. 63. Curves of protracted oxidation of molybdenum disilicide in air at temperatures of 1200-1400° [67]:

1 - weight gain, g/m²;
2 - hours.

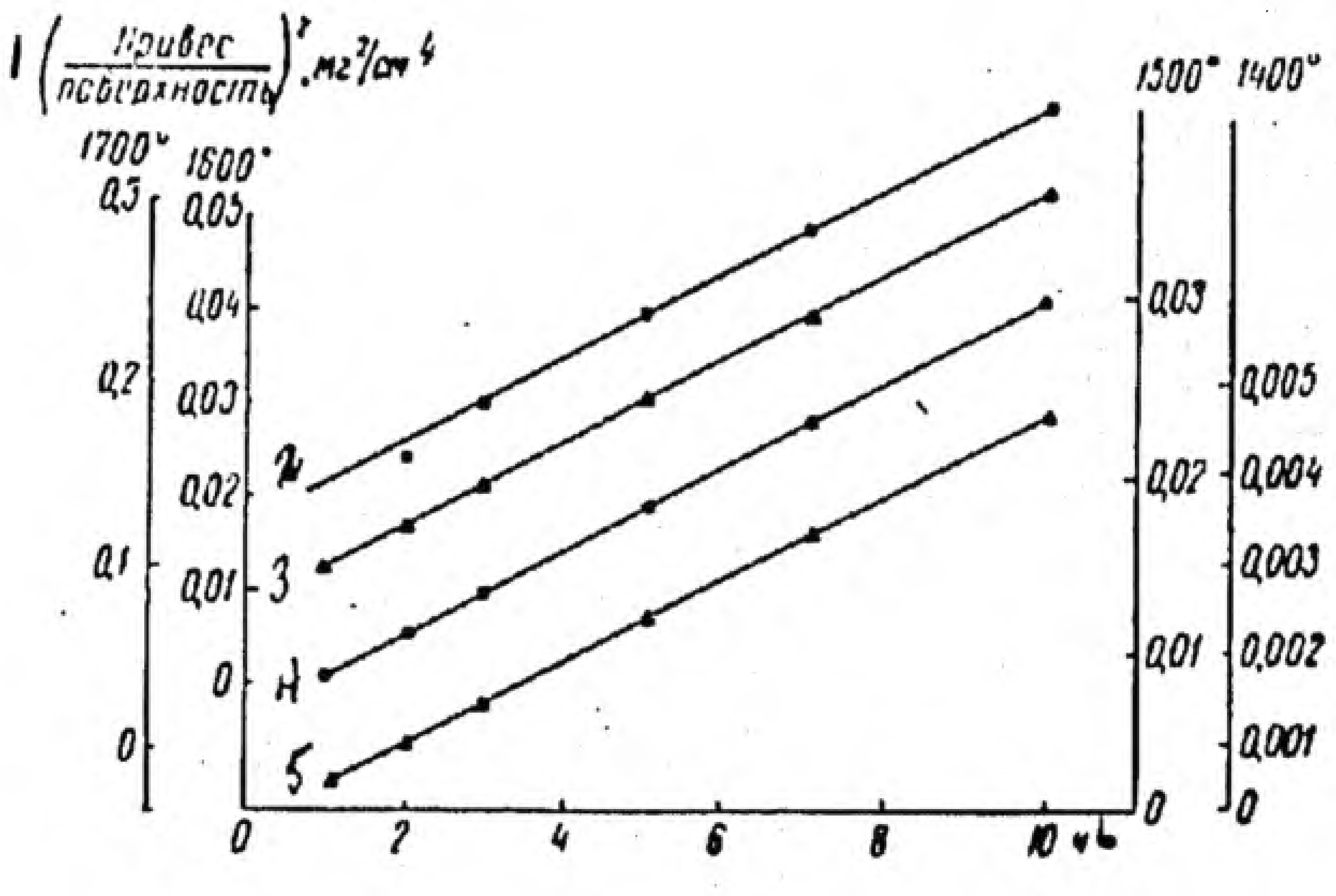


Fig. 64. Curves of oxidation of molybdenum disilicide in air at temperatures of 1400-1700° [64]:

1 - (weight gain/surface)², mg²/cm⁴;
2 - 1700°;
3 - 1600°;
4 - 1500°;
5 - 1400°;
6 - hours.

Curves of protracted oxidation of pure molybdenum disilicide at 1220--1400° are shown in Fig. 63. It is characteristic that when it is heated to 1400° there is initially observed a sharp increase in weight due to formation of a film of silicon dioxide. The protective action of the film is subsequently manifested and the weight gain of the $MoSi_2$ virtually ceases. At 1200° the process of formation of the protective film is slower.

The kinetics of oxidation ofmolybdenum disilicide in air at 1400-1700° at intervals of 100° for 10 hours is illustrated in Fig. 64. It is to be seen from the figure that in the system of coordinates, square of specific gravity versus time, the pattern of oxidation of molybdenum disilicide in time within the temperature range indicated is expressed by straight lines, that is, its oxidation rate is subordinate to the parabolic law.

According to certain data [64], at high temperatures when the test period is lengthened, the film of molybdenum disilicide becomes denser as a result of removal of the volatile oxide MoO_3; this must lead to a logarithmic oxidation pattern. Along with resistance to oxidation, molybdenum disilicide is characterized by high mechanical strength at temperatures up to 1200° and less reduction in strength at temperatures above 1000° in comparison with the titanium-carbide cermet TiC.

Molybdenum disilicide is a substance of medium hardness which is brittle at room temperature. However, at elevated and high temperatures it lends itself well to plastic deformation. Molybdenum disilicide possesses good thermal conductivity, and is consequently thermostable under abrupt temperature changes. The high electrical resistance of molybdenum disilicide has caused it to be used basically for the heater elements of electric furnaces. The service life of heater elements of molybdenum disilicide, $MoSi_2$, is 3250 hours at a surface temperature of 1700° [67].

Another distinctive feature of molybdenum disilicide is its stability toward the action of fused metals, which do not form durable silicides. Fused lead, tin, and sodium do not react with $MoSi_2$ on heating to 1000°. On heating to 800° zinc dissolves up to 1% Si. Fused silver and mercury also have virtually no effect on $MoSi_2$. Fused aluminum actively reacts with $MoSi_2$, forming molybdenum aluminide.

Iron, copper, chromium, and platinum, which form unstable silicides, react with $MoSi_2$ to form binary and ternary silicides.

Molybdenum disilicide is insoluble in all mineral acids, including hydrofluoric acid and aqua regia, but dissolves readily in a mixture of nitric and hydrofluoric acids and is decomposed by fused alkalis.

Tungsten disilicide, WSi_2, approximates molybdenum disilicide in scale resistance. A protective self-reducing film is formed with this silicide as with $MoSi_2$.

Vanadium silicides VSi_2 possess a relatively low scale resistance.

When they are heated in an oxidizing atmosphere, there is formed on them a readily fusible oxide layer which flows off the surface; when this occurs, the surface is bared and oxidized.

The most highly oxidation-resistant of the vanadium silicides is VSi_2.

When heated, the silicides of niobium become heavily oxidized and an easily separated scale is formed.

Materials Of Sintered Aluminum Powder (SAP)

Special note must be made of the metal-ceramic material sintered aluminum powder, the composition and properties of which are given below:

Properties of sintered aluminum powder having a composition of 10-15% Al_2O_3 and the balance aluminum powder [54, 57, 70]:

Specific gravity, g/cm^3	2.8
Scale resistance, °C	350-500
Specific electrical resistance, ohm · mm^2/m	0.23-0.25
Linear expansion coefficient at 20-200° X 10^6	20-22
Ultimate tensile strength, σ_V, kG/mm^2	32-36
Yield point, σ_T, kG/mm^2	23-27
Elongation, ϵ, %	6-8
Brinell hardness, HB	100-110
Modulus of elasticity, kG/mm^2	7,200-7,500

SAP represents a sintered mixture of aluminum powder and the aluminum oxide Al_2O_3. It is designed for the production of semiproducts and parts operating at temperatures of 350-500°. At room temperature the strength of SAP is lower than that of aluminum, but is higher when heated to 350--500° [54]. Within the temperature range indicated, the strength of SAP does not change with increase in the exposure to 1000 hours. The strength of sintered aluminum powder is considerably higher than that of aluminum.

The mechanical properties of SAP depend basically on the particle size of the initial material, aluminum powder. The highest mechanical properties are possessed by articles produced from finely divided aluminum powder having particle sizes smaller than 1μ.

The corrosion resistance of SAP under atmospheric conditions and in the presence of acids is the same as that of pure aluminum.

SAPs are produced in the form of sheets, rods, sections, pipes, forgings, and stampings, and stamped and forged blanks are employed in the automobile and aircraft industries for the manufacture of pistons and compressor blades; and sections, pipes, sheets, and forgings are employed in the mechanical engineering and electrical engineering industries for sealing rings, heat exchangers, and various parts of machinery and apparatus of the chemical industry operating at temperatures above 200° [54, 57, 70].

SAP may be ground, polished, straightened, and anodized in accordance with the procedure customary for aluminum alloys.

6. THERMOSTABLE PLASTICS

Thermostable materials have also been employed in industry along with oxidation-resistant metal, ceramic, and metal-ceramic materials. Above all such materials include plastics.

Plastic materials consist of a binding substance (artificial resin, esters, celluloses, etc.), a filler, and plasticizers. In addition to the components indicated, dyes, stabilizers, inhibitors, and other special additives are introduced into a plastic.

Plastic materials possess a number of valuable physico-mechanical and chemical properties; low specific gravity (1.4 g/cm^3 on the average), high electric, thermal, and sound insulating properties, damping capacity, simplicity of conversion into finished products, stability toward aggressive media, and high antifriction or friction properties.

A fundamental disadvantage of plastic materials is their tendency toward aging, change in physico-mechanical properties with time.

The heat distortion strength of the plastic materials employed in industry is relatively low. The operating temperature of the majority of thermostable plastics is 100-150°; it reaches 250-300° for certain materials. They may be heated to higher temperatures in use for brief periods.

Methods Of Determining The Heat Distortion Strength And Heat Resistance of Plastic Materials

The heat distortion strength of plastic materials is determined by the Martens and Vick methods (GOST 9551-60), etc.

With the first method, heat distortion strength tests are conducted on a Martens tester, a diagram of which is shown in Fig. 65. A sample 1 of the material being tested (formed or laminar) is secured in clamps 2 and 3 and is subjected to the action of a bending moment created by lever 4 on which is situated weight 5. The bending moment must create in the sample a stress equalling 50 kG/mm^2. The test sample is produced in rectangular shape of a cross-section of 15 ± 0.2 X 10 ± 0.2 mm, and of a length of 120 ± 2 mm.

The Martens tester, with the sample mounted, is inserted in a thermostat and subjected to heating at a constant rate of temperature increase equalling 50° per hour. The temperature is monitored by means of a thermometer mounted level with the center of the sample. The amount of deflection of the sample is measured by the displacement of the pointer of indicator 6, which is rigidly connected with the end of the lever.

The temperature at which the end of the lever is lowered 6 mm is adopted as the Martens temperature.

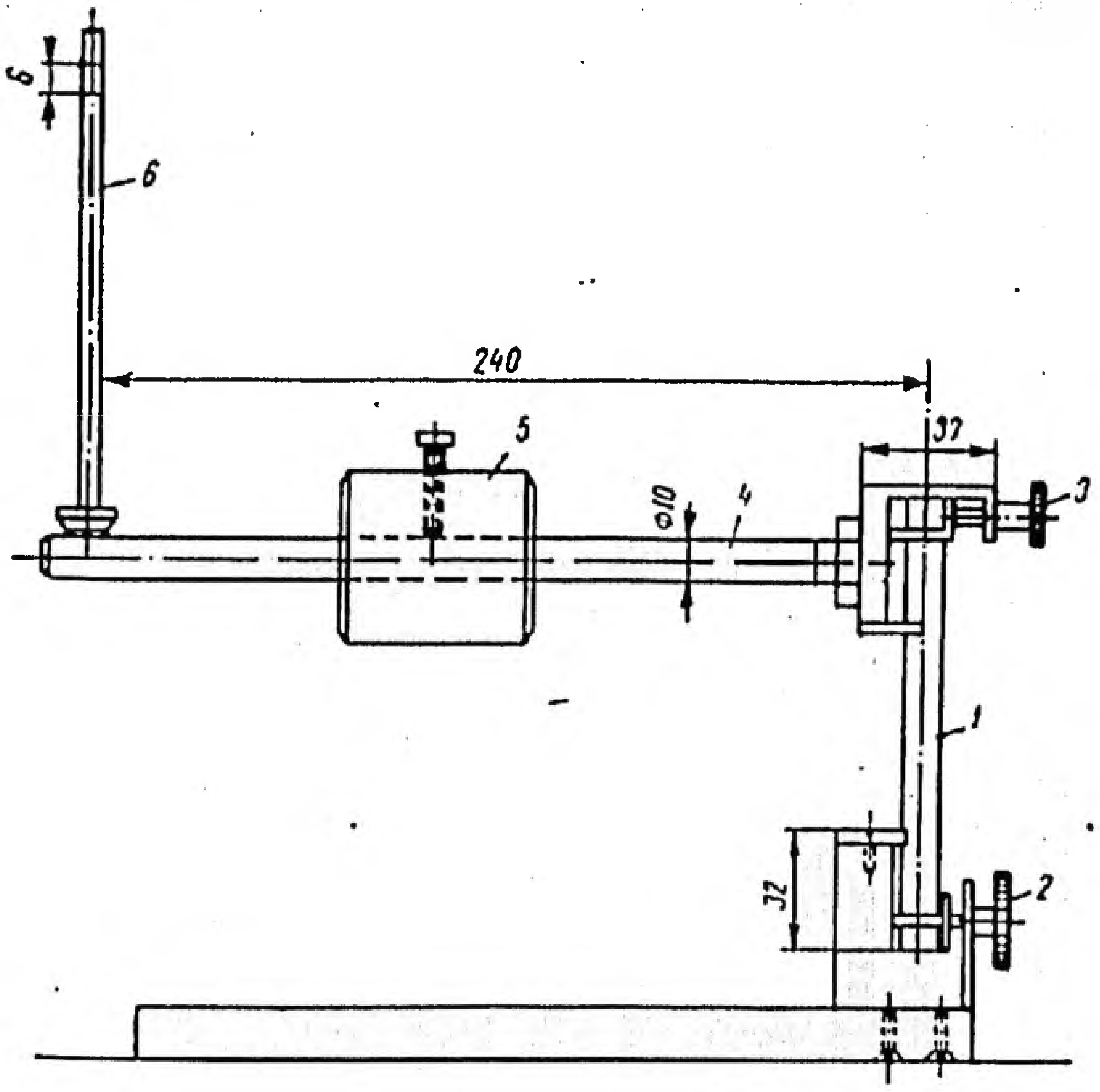


Fig. 65. Diagram of Martens tester for testing heat distortion strength [5]. :

Heat distortion strength is determined by the Vick method on the device, a diagram of which is shown in Fig. 68.

Cylindrical indenter 2, of a cross-sectional area of 1 mm^2 and mounted in rod 3, is pressed into the sample to be tested 1, which is no less than 3 mm thick. By means of a loading device 4, there is transmitted to the sample a load equalling 1000 ± 10 g or 5000 ± 10 g. The load is selected in keeping with the specifications for the material being tested. The amount of deformation of the sample is measured by a special indicator or indicator head.

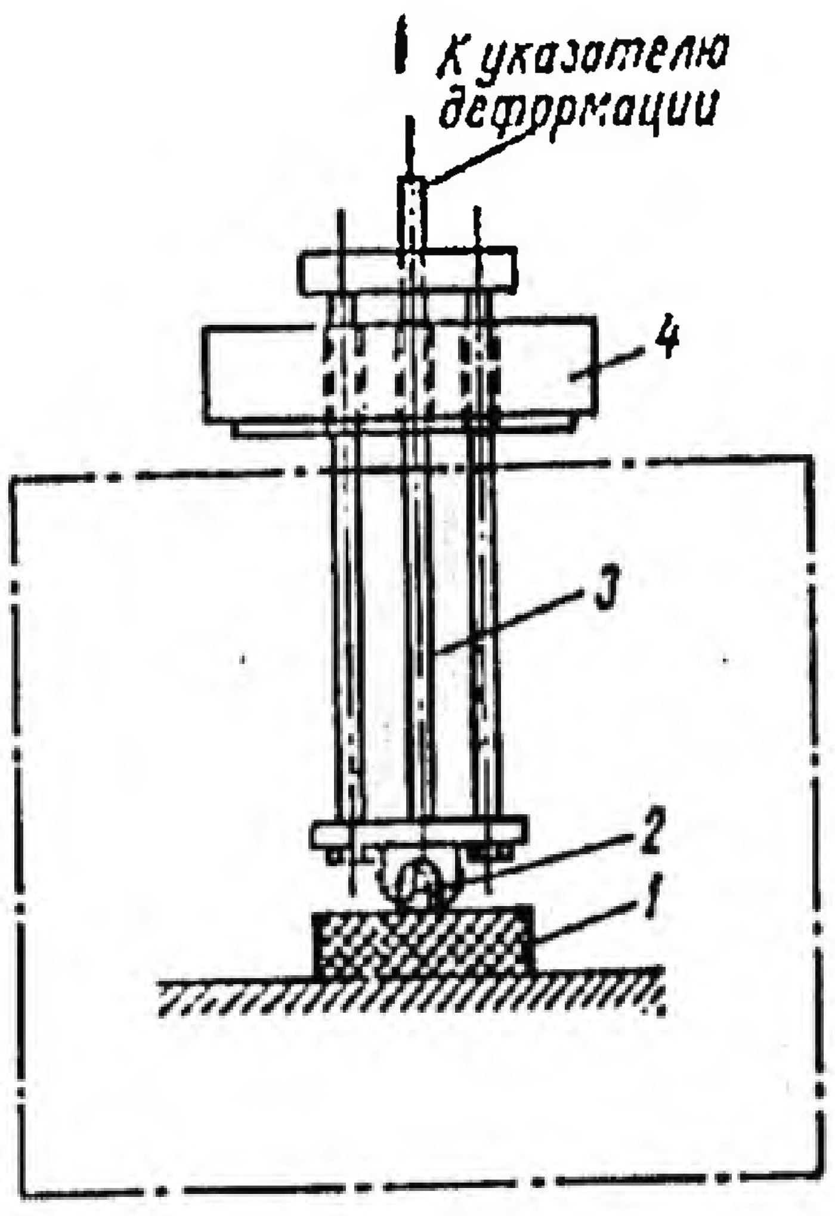


Fig. 66. Diagram of Vick heat distortion strength tester [5]:

1 - To deformation indicator.

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The Vick tester with the sample to be tested is placed in a thermostat and subjected to heating at a constant rate equalling 50 ± 5° per hour. The samples must be no less than three in number. Two thermocouples are installed in the thermostat for monitoring the temperature of the sample to be tested.

The temperature at which the indenter makes an indentation in the tested sample of plastic material to a depth of 1mm is adopted as the Vick temperature. The Vick method is not applicable for heterogeneous materials (such as laminated plastics, etc.).

The Schramm heat resistance is determined by the length of the burnt portion and weight loss of a tested sample as a result of contact of the latter with a silite rod incandesced to 950°. The heat resistance of pressed, formed, and laminar materials of plastics of organic origin (OST NKTP 3081) is determined by this method.

The sample to be tested is in the form of a plate 120 ± 2 mm long, 15 ± 2 mm wide, and 3 ± 0.2 mm thick. The silite rod of the Schramm tester must have a length of 170 ± 2 mm and a diameter of 7.7 ± 1 mm.

The burnt portion of the sample is determined by weighing the latter and measuring its length before and after holding in contact with the incandescent silite rod for 3 minutes.

The product of multiplication of the length of the burnt portion of a sample, l (in cm), by the weight loss, q (in mg), is adopted as the Schramm heat resistance. The heat resistance is determined by a six-point system (Table 52).

Table 52

Amount Of Heat Resistance

Conventional Schramm heat resistance figure, lq	Conventional heat resistance rating
More than 100,000	0
100,000 -- 10,000	1
10,000 -- 1,000	2
1,000 -- 100	3
100 -- 10	4
Less than 10	5

Physicomechanical Properties

The physical and mechanical properties of thermostable plastic materials employed in industry are given in Tables 53 and 54. Only those materials the Martens temperature of which is higher than 100 °C are considered in these tables. They include polystyrene, polytetrafluoroethylene, phenoplasts, hardened paper, textolite, amino and aniline plastics, silicone resins, and fiberglass-reinforced plastics.

Polystyrene represents a product of polymerization of styrene. It possesses a number of valuable properties: exceptionally high water resistance, chemical stability, and highdielectric properties, and it lends itself readily to redesigning into manufactured articles.

The basic disadvantages of articles of polystyrene are combustibility and a tendency to crack. The latter is due to the occurrence of internal stresses on abrupt changes in temperature in the forming process. This disadvantage is partly eliminated by post-annealing.

The heat-distortion temperature of the majority of the brands of polystyrene is relatively low: 70-90°. With polystyrene of brands PMKhS (emulsion and filled) and PDKhS the Martens temperature is somewhat higher than 110°. They are employed basically for the manufacture of parts of high-frequency insulation.

Polytetrafluoroethylene(ftoroplast-4) represents a product of polymerization of tetrafluoroethylene gas $CF_2 = CF_2$. In the United States this plastic is designated as teflon.

Polytetrafluoroethylene is a fibrous, finely ground material of a dull white color; in manufactured articles it has the form of a white mass with a greasy, slippery surface.

Polytetrafluoroethylene crystallizes at a temperature of 260-310°; above 327° it passes into an amorphous state. Above 415° the plastic decomposes without passing into a viscous state. For this reason articles of polytetrafluoroethylene are manufactured in tablets when cold under a pressure 300-350 kG/cm^2, with subsequent sintering of the tablets at a temperature of 375 ± 10°, since pressing accompanied by heating and casting under pressure are inapplicable in this case [5, 17].

The special properties inherent in polytetrafluoroethylene have caused it to be widely used in industry. It is not wetted and does not swell in water. In chemical stability it excels gold and platinum [5]; it is stable toward all mineral and organic acids; it decomposes only under the action of fused alkali metals and elementary fluorine. Polytetrafluoroethylene is absolutely insoluble in all known solvents, with the exception of fluorinated kerosene. Articles of this plastic may be employed at temperatures up to 250°. However, at these temperatures it is characterized by high flowability (creep), which increases with elevation of the temperature (Table 55). This is its chief disadvantage.

Ftoroplast-4 can be welded only by use of a flux consisting of 65 parts by weight of carbon tetrafluoride oil and 35 parts by weight of ftoroplast powder. The surfaces to be welded, first smeared with the flux, are compressed under a pressure of 2.5-3.5 kG/cm^2 and heated to 360-380°.

Ftoroplast-4 does not lend itself to gluing by conventional methods because of the chemical inertness of its surface.

The phenoplasts or formaldehyde resins and plastics represent products of polycondensation of phenols and formaldehyde. The phenoplasts are obtained by mixing phenolformaldehyde synthetic resins with fillers, hardening agents, and other substances.

Two forms of phenoplasts are distinguished: resols and thermoplastics. Resol (thermosetting) bakelite resins are obtained by employing trifunctional phenols. The resins are formed by polycondensation of formaldehyde with a molecular rationof phenol to formaldehyde of 5:6 or 6:7 in an alkaline medium with an excess of formaldehyde.

Thermoplastic resins are obtained on the basis of trifunctional or non-functional phenols. The resin is formed by polycondensation of the phenol with a molecular ratio of phenol to formaldehyde of 6:5 or 7:6 in an acid medium with an excess of phenol.

Table 53

Thermostable Plastic Materials

Designation of material	GOST or specification	Specific gravity, g/cm^3	Martens temperature, $^{\circ}C$	Water absorption in 24 h, g/dm^3
Polymers of unsaturated hydrocarbons				
Polystyrene Kh PMKhS - emulsion type	TU 585-59	1.28-1.4	110	0.01-0.03
Polystyrene Kh PMKhS - filled	VTU GKhPK M529-59			
Polystyrene PDKhS	TU 254-54			
Polymers of halogen derivatives of ethylene				
Ftoroplast--4 (Polytetrafluoroethylene)	TU MKhP M162-54; VTU FP4-59 of brands A, B, and V; TU M191-57	2.1-2.4	250	0.0
Phenoplasts				
Molding compound (molding powder)General purpose types: 0.1; 0.2; 0.3; 0.4	GOST 5689-60	1.4-1.5	125	0.1-0.2
Same, special type, ammonia-free Sp1, Sp2	GOST 5689-60	1.4-1.95	125-150	0.03-0.1

Table 53 (Cont'd)

Designation of material	GOST or specification	Specific gravity, g/cm^3	Martens temperature, °C	Water absorption in 24 h, g/dm^3
Same, electric insulating type E1, E2, E3	GOST 5689-60	1.4-1.8	120-125	0.05-0.08
Same, high-frequency type Vch2, Vch1	GOST 5689-60	1.9-1.95	125-150	0.03
Same, moisture and chemically stable type Vkh1, Vkh2, Vkh3, Vkh4	GOST 5689-60	1.5-1.7	125	0.03-0.05
Same, impact-resistant coarse fiber type V11, V12, V13	GOST 5689-60	1.45-1.95	140-200	0.4-0.5
Same, heat-resistant type Zh1, Zh2, Zh3	GOST 5689-60	1.75	140-150	0.03.0.05
Same, molding material of brands: K-217-57P K-41-5 K-F-3, K-F-3-M	VTU MkhP M752--57 VTU MKhP 4386-55 TU MKhP 37-57 TU MKhP 4155-54	1.7-1.95	200	0.25-0.7
Diced textolite board of brands A and B	TU MKhP M670-55	1.3-1.4	125	1.0
Hardened paper of brands A, B, V, D, Vs, Av, Bv, Vv, Gv, Dv, (for high frequencies)	GOST 2718-54 (all brands)	1.25-1.4	150	0.45-0.7
Textolite of brands PTk, PT, and PT-1	GOST 5-52 (all brands)	1.3-1.4	125	0.35-0.65
Sheet electrical engineering textolite of brands A, B, V, G, ST	GOST 2910-54 (all brands)	1.3-1.85	125-185	0.28-0.6

Table 53 (Cont'd)

Designation of material	GOST or specification	Specific gravity, g/cm^3	Martens temperature, °C	Water absorption in 24 h, g/dm^3
Metallurgical textolite of brand B	TU MKhP 4184-54	1.3-1.4	120	0.7
Asbotextolite of brands A and B	TU MKhP 2548-51 (all brands)	1.6	250	2.0
Amino and aniline plastics				
Melamine molding powders of brands K-77-51 K-78-51	TU MKhP 3883-53 TU M559-54	1.6-1.8	150	0.1
Moldingmaterials of brands VEI-11, VEI-12, K-79-79 (melamite)	TU MKhP M692-56 TU MKhP 371-55 TU MKhP M733--56	--	150	--
Silicone resins				
Asbovoloknit K-41-5	VTU MKhP 4386-55	1.9	200-300	0.25
Molding material KMK-218	TU MKhP P63--57	1.9	250	0.31
Molding powder KMK-9	TU MKhP Sh39-55	--	200	0.25
Hot hardening fiberglass reinforced plastics				
Glass textolite of brand KAST	TU MKhP M682-56 (all brands)	Weight of 1 m^2 1.2 mm thick: 2 kg	200	0.15-0.35
Glass textolite of brand KAST-1	TU MKhP M682-56 (all brands)	2-2.2	200	0.5-1.5
Glass textolite of brands KAST-15 KAST-K KAST-P	TU MKhP M285-54	Weight of 1mm^2 30 mm thick: 60 kg	190-200	—
Glass textolite of brand KAST-V, 0.5 to 5.5 mm thick	VTU M697-57	Weight of 1 m^2 2.5 mm thick: 4 kg	200-210	0.8-1.5%

Table 53 (Cont'd)

Designation of material	GOST or specification	Specific gravity, g/cm^3	Martens temperature, $^\circ$C	Water absorption in 24 h, g/dm^3
Glass textolite of brand KAST-VK	VTU-MKhP M757-57	---	200-210	1.0
Glass textolite of brand ST	GOST 2910-54	1.7-1.8	185	---
Glass textolite of brands STK-1-A STK-1-B	TU 41-6-56 (of "Electroizolit" Plant)	1.6-1.8	200--250	---

Designation of material	Electrical resistance, ohm • cm	Combustibility	Use
Polymers of unsaturated hydrocarbons			
Polystyrene Kh PMKhS - emulsion type	$1 \cdot 10^{15}$ $2 \cdot 10^{16}$	Burns with dying flame	High-frequency insulation parts
Polystyrene Kh PMKhS - filled			
Polystyrene PDKhS			
Polymers of halogen derivatives of ethylene			
Ftoroplast -4 (Polytetrafluoroethylene)	$1 \cdot 10^{19}$	Does not burn	Electrical insulation of high-frequency wires and cables, electrical insulating parts, sealing articles (liners, seats), anti-corrosion lining stable toward chemical regents; anti-friction parts
Phenoplasts			
Molding compound (molding powder) General-purpose types: 0.1; 0.2; 0.3; 0.4	$1 \cdot 10^{11}$	Difficult to ignite and dies out outside of flame	Various hardware articles, accessories, parts of electric illuminating fittings and parts used in telephony, articles of increased impact

Table 53 (Cont'd)

Designation of material	Electrical resistance, ohm • cm	Combustibility	Use
			strength, miscellaneous small articles, handles etc.
Same, special type, ammonia-free Sp1, Sp2	$5 \cdot 10^{12}$ $5 \cdot 10^{13}$	Difficult to ignite and dies out outside flame	Electrical engineering articles with high dielectric properties
Same, electric insulating type E1, E2, E3	$5 \cdot 10^{12}$--- $5 \cdot 10^{13}$		Electrical engineering, electrical insulating, radio parts, etc.
Same, high-frequency type Vch1, Vch2	$1 \cdot 10^{14}$		High-frequency dielectric
Same, moisture and chemically stable type Vkh1, Vkh2, Vkh3, Vkh4	$1 \cdot 10^{11}$ --- $5 \cdot 10^{13}$		Acid-resistant, alkali-resistant, and anti-corrosion articles
Same, impact-resistant coarse fiber type V11, V12, V13	$1 \cdot 10^{9}$ --- $1 \cdot 10^{10}$		Articles of high mechanical strength and impact-resistant articles
Same, heat-resistant type Zh1, Zh2, Zh3	$1 \cdot 10^{9}$ --- $5 \cdot 10^{12}$		Electrical installation parts
Same, molding material of brands: K-217-57P K-41-5 K-F-3, K-F-3-M	$3.5 \cdot 10^{7}$--- $1 \cdot 10^{10}$	Does not burn	For brake shoes and other articles for which high thermal stability requirements are set
Diced textolite board of brands A and B	$1 \cdot 10^{10}$		Electrical insulating, anti-friction, and other articles
Hardened paper of brands A, B, V, D, Vs, Av, Bv, Vv, Gv, Dv (for high frequencies)	$1 \cdot 10^{9}$--- $1 \cdot 10^{12}$	Difficult to ignite and dies out outside flame	Panels of electric distributing devices, insulating liners, and other electrical insulating parts
Textolite of brands PTk, PT, and PT-1	$1 \cdot 10^{10}$-- $1 \cdot 10^{12}$		Liners, gears, anti-friction bushings of bearings, and other parts

Table 53 (Cont'd)

Designation of material	Electrical resistance, ohm • cm	Combustibility	Use
Sheet electrical engineering textolite of brands A, B, V, G, ST	$1 \cdot 10^9$ $1 \cdot 10^{10}$	Difficult to ignite and dies out outside flame	Electrical engineering parts operating in transformer oil and in air, parts of radio equipment, panel; at temperatures of 60-125° for textolite of brand ST
Metallurgical textolite of brand B	----		Bearing bushings of rolling mills
Asbotextolite of brands A and B	----	Does not burn	Friction parts and liners operating at elevated temperatures
Amino and aniline plastics			
Melamine molding powders of brands K-77--51 K-78-51	$1 \cdot 10^{13}$	Dies out after source of fire is removed	Electrical engineering parts, ignition devices, monarcing electrical insulating parts
Molding materials of brands Vel--11, Vel-12, K-79-79 (melamite)	$1 \cdot 10^{10}$ $1 \cdot 10^{11}$		Nonarcing electrical engineering parts
Silicone resins Asbovoloknit K-41-5	10^{10}	Scarcely burns	Housings and parts of electric fitting devices and electrical equipment heated to 200° and higher
Molding material KMK-218	$1 \cdot 10^9$ $1 \cdot 1^{10}$	Scarcely burns	Parts requiring nonarcing properties and thermal stability
Molding powder KMK-9	10^{14}	Does not burn	Parts of electric and radio instruments and mechanisms requiring high electric insulating properties and thermal stability
Hot hardening fiberglass reinforced plastics			
Glass textolite of brand KAST	10^{13}-10^{14}	Does not burn	Thermostable structures of high mechanical strength

Table 53 (Cont'd)

Designation of material	Electrical resistance, ohm • cm	Combustibility	Use
Glass textolite of brand KAST-1	10^{13}-10^{14}	Does not burn	Thermostable structure of high mechanical strength
Glass textolite of brands KAST-15 KAST-K KAST-P	----		Elements of structures requiring increased impact resistance
Glass textolite of brand KAST-V, 0.5 to 5.5 mm thick	---		Elements of structures requiring high mechanical strength and water resistance
Glass textolite of brand KAST-VK	----		Various structures
Glass textolite of brand ST	10^{12}		Electrical engineering material for operation in air at temperatures of -60 to 180°
Glass textolite of brands STK-1-A STK-15	10^{12}		Electrical engineering materials employed at temperatures of -60 to 180°

Table 54

Thermostable Plastic Materials Mechanical Properties

Designation of material	GOST or specification	Ultimate strength σ_v, kG/cm^2			
		tensile	bending	compressive	shearing
Polymers of unsaturated hydrocarbons					
Polystyrene Kh-PMKhS - emulsion type	TU 585-59	350-400	350-500	1000	---
Polystyrene Kh-PMKhS - filled	VTU GKhPK M529--59				
Polystyrene PDKhS	TU 254-54				
Polymers of halogen derivatives of ethylene					
Ftoroplast--4 (polytetrafluoroethylene)	TU MKhP M162-54	160-250	110-140	--	---
Ftoroplast-4 (of brand 4)	FP4-59				

Table 54 (Cont'd)

Designation of material	GOST or specification	Ultimate strength σ_v, kG/cm^2			
		tensile	bending	compressive	shearing
Phenoplasts					
Molding compound (molding powder) General-purpose types: 0.1; 0.2; 0.3; 0.4	GOST 5689-60	300-450	500-600	1400-1500	--
Same, special type, ammonia-free, Sp1, Sp2	GOST 5689-60	280	500-600	1400	--
Same, electric insulating type E1, E2, E3	GOST 5689-60	280-530	600-700	1400	—
Same, high-frequency type Vch1, Vch2	GOST 5689-60	280	550-850	1100	---
Same, moisture and chemically stable type Vkh1, Vkh2, Vkh3, Vkh4	GOST 5689-60	---	450-600	1500	---
Same, impact-resistant coarse fiber type V11, V12, V13	GOST 5689-60	300	800	1200	—
Same, heat-resistant type Zh1, Zh2, Zh3	GOST 5689-60	—	400-500	----	-----
Diced textolite board of brands A and B	TU MKhP M670-55	250	500-600	1400	-----
Molding material of brands: K-217-57P K-41-5 K-F-3, K-F-3-M	VTU MKhP M752-57 VTU MKhP 4386--55 TU MKhP 37-57 TU MKhP 4155-54	----	500--700	800-1325	------
Hardened paper of brands A, B, V, Vs, G, D, Av, Bv, Gv, Dv (for high frequencies)	GOST 2718-54 (all brands)	700-1000	800-1400	---	150-200

Table 54 (Cont'd)

Designation of material	GOST or specification	Ultimate strength σ_v, kG/cm²			
		tensile	bending	compressive	shearing
Textolite of brands PTK, PT, PT-1	GOST 5-52 (all brands)	650-1000	200-1600	2000-2500	---
Sheet electrical engineering textolite of brands A, B, Vch, G, ST	GOST 2910-54 (all brands)	400--700	900-1200	----	130-300
Metallurgical textolite of brand B	TU MKhP 4184-54	—	—	900 parallel to layers	300 spalling
Asbotextolite of brands A and B	TU MKhP 2548-51 (all brands)	800	1000-1700	850-1000	—
Amino and aniline plastics					
Melamine molding powders of brands K-77-51 K-78-51	TU MKhP 3883-53 TU M559-54	---	500	-----	-----
Material of brands VEI-11 VEI-12 K-79-79	MKhP M692-56 TU MKhP 371-55 TU MKhP M733-56	---	200-600	------	-----
Silicone resins					
Asbovoloknit K-41-5	VTU MKhP 4386-55	230	500	1325	—
Molding material KMK-218	TU MKhP P63-57	---	300	---	------
Molding powder KMK-9	TU MKhP 1P39-55	---	300	----	-------
Hot hardening fiberglass reinforced plastics					
Glass textolite of brand KAST-1	TU MKhP M682-56 (all brands)	2700-2800 along warp 1500-1700 along weft	---	-----	-------
Glass textolite of brands KAST-15 KAST-K	TU MKhp M285-54	2600 along warp, 1500 along weft	1000 parallel to layers, 2700 perpendicular to layers	----	400 along warp, 300 along weft

Table 54 (Cont'd)

Designation of material	GOST or specification	Ultimate strength σ_v, kG/cm²			
		tensile	bending	compressive	shearing
Glass textolite of brands KAST-P	TU MKhP M285-54	1000 along weft	600 parallel to layers 2500 perpendicular to layers	---	
Glass textolite of brand KAST-V, 0.5 to 5.5 mm thick	VTU MKhP M697-57	2500 along warp 1500 along weft	1265	1000 parallel to layers	150-170 spalling
Glass textolite of brand KAST-VK	VTU MKhP M757-57	1500	----	3000	-----
Glass textolite of brand ST	GOST 2910-54	1200	1200	----	130 spalling
Glass textolite of brands STK-1-A STK-1-B	TU 41-6-56 (of "Electroizolit" Plant)	100-2500	1100	-----	100-300 spalling

Designation of material	Specific impact toughness*, kG • cm/cm²	Modulus of elasticity in tension, kG/cm²	Brinell hardness, HB
Polymers of unsaturated hydrocarbons			
Polystyrene Kh-PMKhS - emulsion type	2,5-4.5	14,000-32,000	18-21
Polystyrene Kh-PMKhS - filled			
Polystyrene PDKhS			
Polymers of halogen derivatives of ethylene			
Ftoroplast-4 (Polytetrafluoroethylene)	>100	3859-4550	3-4
Ftoroplast-4 (of brand 4)			

Table 54 (Cont'd)

Designation of material	Specific impact toughness* kG • cm/cm^2	Modulus of elasticity in tension, kG/cm^2	Brinell hardness, HB
Phenoplasts			
Molding compound (molding powder) General-purpose types: 0.1; 0.2; 0.3; 0.4	5.0-9.0	70,000-90,000	20-25
Same, special type, ammonia-free, Sp1, Sp2	4.5	------	20--25
Same, electric insulating type E1, E2, E3	4.5-5.0	63,000-88,000	20-25
Same, high-frequency type Vch1, Vch2	3.5-5.0	------	20-25
Same, moisture and chemically stable type Vkh1, Vkh2, Vkh3, Vkh4	4.5-8.0	-------	27-31
Same, impact-resistant coarse fiber type V11, V12, V13	9.0-20.0	-------	------
Same, heat-resistant type Zh1, Zh2, Zh3	3.0-4.5	---------	-------
Diced textolite board of brands A and B	9.0-21.0	85,000	0------
Molding material of brands: K-217-57P K-41-5 K-F-3, K-F-3-M	9.0-21.0	------	19-30
Hardened paper of brands A, B, V, Vs, G, D, Av, Bv, Gv, Dv (for high frequencies)	13.0-20.0	-------	-------
Textolite of brands PTK, PT, PT-1	25-35	------	-------

Table 54 (Cont'd)

Designation of material	Specific impact toughness* kG • cm/cm^2	Modulus of elasticity in tension, kG/cm^2	Brinell hardness, HB
Sheet electrical engineering textolite of brands A, B. Vch, G, ST	20-50	----	----
Metallurgical textolite of brand B	-------	--------	28
Asbotextolite of brands A and B	20-25	140,000-200,000	30--45
Amino and aniline plastics			
Melamine molding powders of brands K--77-51 K--78-51	4.0-4.5	---------	----
Materials of brands VEI-11 VEI-12 K-79-79	1.7-10.0	--------	----
Silicone resins			
Asbovoloknit K-41-5	18.0	--------	19
Molding material KMK-218	4.5	--------	20
Molding powder KMK-9	3.5	--------	28
Hot hardening fiberglass reinforced plastics			
Glass textolite of brand KAST-1	60 along warp, 45 along weft	--------	24-35
Glass textolite of brands KAST-15 KAST-K KAST-P	400 along warp 300 along weft	--------	------
Glass textolite of brand KAST-V, 0.5 to 5.5 mm thick	100 along warp, 75 along weft	200,000	------

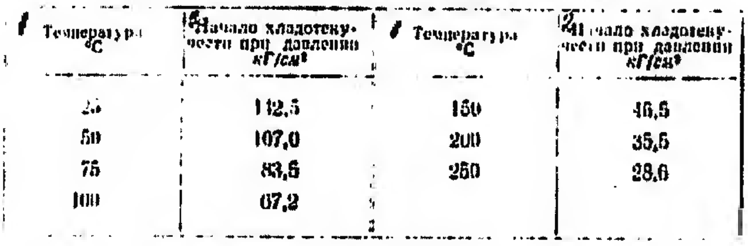
Table 54 (Cont'd)

Designation of material	Specific impact toughness* kG • cm/cm^2	Modulus of elasticity in tension, kG/cm^2	Brinell hardness, HB
Glass textolite of brand KAST-VK	----	------	-----
Glass textolite of brand ST	50	——	——
Glass textolite of brands STK-1-A STK-1-B	50	——	——

*Normal sample (no notching)

Table 55

Cold Flow Of Ftoroplast-4 Versus Temperature And Specific Pressure 5



1 Температура °C	2 Начало хладотекучести при давлении кГ/см²	1 Температура °C	2 Начало хладотекучести при давлении кГ/см²
25	112,5	150	46,5
50	107,0	200	35,5
75	83,5	250	28,6
100	67,2		

1 - Temperature, °C; 2 - Beginning of cold flow at a pressure, kG/cm^2, of: .

The phenoplasts are generally produced in the form of molding (bakelite) powders and molding compounds on the basis of resol and thermoplastic resins.

Information on the various types of phenoplastics of various brands is given in GOST 5689-60.

The Martens temperature of the phenoplasts listed in Table 53 ranges from 120 to 200°. High dielectric and electric insulating properties are characteristic of many brands of phenoplasts.

Getinaks (pertinax) is a laminated plastic material. It consists of sheets of paper impregnated with phenol-formaldehyde resins. Getinaks is produced in the form of sheets and plates 0.5 to 50 mm thick and with dimensions of no less than 450X600 mm (GOST 2718-54).

Getinaks possesses high dielectric properties and satisfactory mechanical strength, and may be employed for the manufacture of gear wheels, plates, liners, power panels, and the like. Articles of getinaks may operate over the -60 to +105° temperature range.

Textolite is a laminated plastic material consisting of cotton fabric (sheeting, chiffon, industrial fabrics, etc.) arranged by layer, impregnated with resol resin, and moulded.

Textolite is produced in sheets and plates up to 70 mm thick, round blocks, rods, pipes, and irregularly shaped articles. Textolite possesses high antifriction properties and higher resistance to compression and specific impact toughness than getinaks.

Textolite is employed for the manufacture of noiseless gear wheels, busings, antifrictions bushings for bearings, support and shock-absorbing wheels, and for various parts of electric equipment: panels, brush holders, terminals, and the like.

The amino plastics (amino-formaldehyde plastics) are products of poly-condensation of urea (carbamide), melamine, and other compounds with formaldehyde.

Plastics based on the products of polycondensation of melamine are characterized by high heat distortion strength, moisture resistance, and mechanical strength, and by better dielectric characteristics than plastics based on urea. The melamine plastics also possess high stability toward surface discharges.

These properties of melamine plastics have determined their utilization in the production of electrical engineering elements: fuses for high-voltage current, ignition devices, and others.

Silicone resins are high-molecular substances based on a chain of silicon atoms alternating with oxygen atoms, the so-called siloxane chain.

Silicone resins possess high electric insulating properties and great thermal stability. The mechanical strength of these resins changes very little over the -50 to 300-350° temperature range.

The chemically stable heat-resistant molding materials asbovoloknit, plastics from which are produced the parts of electric apparatus and electric equipment instruments operating under the conditions of surface discharges and heating up to 200° and above, are obtained in industry on the basis of silicone resins.

Hot hardening fiberglass reinforced plastics (steklotekstolity; glass textolites) are plastics the binding material of which is synthetic resins, including phenolaldehyde resins, and the filler of which is various types of glass cloth. Glass textolites of brands KAST, KAST-1, KAST-0.5, KAST-15, KAST-V, and others are manufactured on the basis of phenolaldehyde resins modified with polyvinylbutyral resin (BF-3, BF-7 and BF-8). Glass textolite is manufactured in the form of sheets 0.5 to 15 mm thick and having dimensions no smaller than 1000-2400 mm. Owing to the presence of glass cloth in the plastic, the strength properties of glass textolite are far higher than those of the ordinary varieties of textolite. The resistance to tension of glass textolite is approximately 1.5 to 2 times greater than that of textolite.

Glass textolite is stable toward the action of impact loads, and possesses low hygroscopicity, good chemical stability, and high dielectric properties.

Various power parts, structural elements requiring increased impact strength, mechanical strength, and thermal stability, and parts of electric equipment with high electric insulating properties are manufactured from glass textolite.

Silicone resins are employed in hot molding plastics, particularly in glass textolite of brand STK. Such fiberglass reinforced plastics possess high arc and spark resistance.

CHAPTER III

OXIDATION-RESISTANT AND THERMOSTABLE PROTECTIVE COATINGS

The stability of the surface of a metal toward oxidation is particularly important at the present-day level of development of technology. Creation of the latest gas turbines, engines, rockets, and other articles and assemblies is determined largely by the oxidation resistance of their parts.

A number of metals (molybdenum, titanium, and others), alloy steels, and alloys possess high mechanical strength when heated, but they are not oxidation-resistant: they suffer intensive oxidation and without additional protection cannot be employed for operation at high temperatures.

A particularly pernicious effect is exerted on metal parts by the combustion products of fuel containing sulfur, lead, vanadium pentoxide, and other aggressive chemical agents; they corrode the surface of the metal. In addition, the surface of metal parts may be extensively damaged by the impacts of hot gases, flame, and the very fine particles of fuel combustion products moving at high velocity; the metal surface is extensively worn as a result of such action.

One of the methods of protecting the surface of metal parts from destruction under the action of elevated or high temperatures is the application of thermostable and oxidation-resistant coatings.

The basic requirements set for oxidation-resistant coatings are (2) capacity to resist corrosion and oxidation; (b) capacity to resist erosion wear; (c) insulation of the base metal of parts against heating.

Both metal (chromium, nickel, aluminum, and others) and non-metallic (ceramic, metal-ceramic, etc.) coatings have been employed as oxidation-resistant coatings.

A. METAL COATINGS

1. CHROMIUM COATINGS

Chromium coating is one of the widespread methods of protecting parts subjected to high temperatures under atmospheric conditions or in the presence of other aggressive media against oxidation. At the same time chromium coatings are characterized by high wear resistance under conditions of friction, and by resistivity to erosion wear accompanied by dependable chemical stability.

Two basic methods are employed in industry for applying chromium coatings: chromium plating and chromizing.

Electrolytic Chromium Coatings

Chromium plating is carried out in electrolytes containing chromium anhydride (150-250 g/l) and sulfuric acid of a specific gravity of 1.84 (1.5-2.5 g/l), at a temperature of 55-70° and a cathode current density of 50-30 a/dm^2. The length of the chromium plating process is determined by the thickness of the coating. The thickness of a chromium coating for steel recommended for protection against oxidation should be no less than 40-60μ.

The protective properties of a chromium coating are determined chiefly by its continuity; in effect the pores in chromium coatings (bright deposits) overlap when the layer thickness is no smaller than 30-40μ. For greater dependability use is sometimes made of two-layer coatings: a milky plus a bright deposit.

The protective action of chromium coatings consists in the formation on their surface when heated of a dense oxide film which protects the metal against further oxidation.

Electrolytic chromium coatings satisfactorily protect steel parts from gas corrosion at temperatures of 600-700° [10, 15].

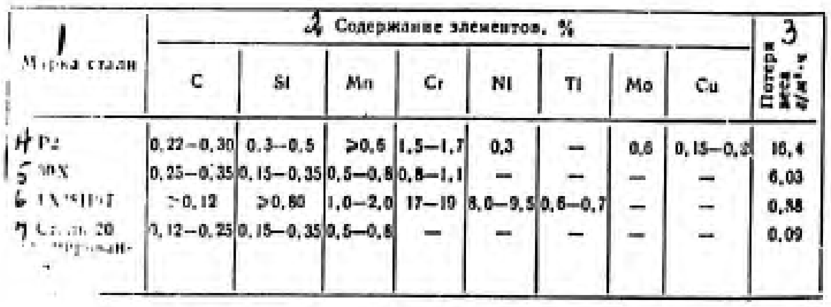
In tests of samples of carbon and alloyed brands of steel within the temperature range in question for 1500-4000 hours in an atmosphere of air [58], as well as in a mixture of air, sulfur dioxide (0.5%), carbon dioxide (2.4%), and superheated steam [15], the change in the weight of the chromium-plated samples amounts to 0.006-0.015 g/m² • h. Such weight change attests to the good oxidation resistance of chromium-plated parts. In the process of operation at high temperatures there is formed on the chromium coating a tight film of oxides brown in color under which a bright layer of metallic chromium is usually preserved.

Electrolytic chromium coatings are also characterized by satisfactory thermal stability; they withstand 10 thermal cyclings from a temperature of 750° and subsequent cooling in tap water (water temperature 8-10°) without flaking off and failure [58].

The interaction of electrolytic chromium coatings with vanadium pentoxide is of interest (Table 56). Considerable amounts of the latter are contained in the ashes of certain mineral fuels. Vanadium pentoxide fosters acceleration of the gas corrosion of oxidation-resistant steels and alloys.

Table 56

Comparative Data On The Weight Loss Of Chromium-Plated Steel 20 And Certain Other Brands Of Steel After Tests In Contact With V_2O_5, Temperature 700°, Test Period 550 Hours [15]



1 Марка стали	2 Содержание элементов, %								3 Потеря веса, г/м²·ч
	C	Si	Mn	Cr	Ni	Ti	Mo	Cu	
4 Р2	0,22—0,30	0,3—0,5	≥0,6	1,5—1,7	0,3	—	0,6	0,15—0,2	16,4
5 30Х	0,25—0,35	0,15—0,35	0,5—0,8	0,8—1,1	—	—	—	—	6,03
6 1Х18Н9Т	≥0,12	≥0,80	1,0—2,0	17—19	8,0—9,5	0,6—0,7	—	—	0,88
7 Сталь 20 хромированная	0,12—0,25	0,15—0,35	0,5—0,8	—	—	—	—	—	0,09

1 - Brand of steel;
2 - Content of elements;
3 - Weight loss, g/m² • h;
4 - R2;
5 - 30Kh;
6 - 1Kh18N9T
7 - Chromium-plated steel 20.

It is to be seen from the table that steels of brands R2 and 30Kh suffer extensive destruction when in protracted contact with V_2O_5 at 700° and are almost completely converted into scale. A scale which can easily be peeled off the base metal is formed on steel 1Kh19N9T. A thin brown crumbling oxide film is formed on the chromium coating of steel 20; under the oxide film there is a bright dense layer of metallic chromium.

The weight loss of chromium-plated steel 20 in contact with vanadium pentoxide for 550 hours at 700° is 10 times less than that of oxidation-resistant steel 1Kh19N9T, and hundreds of times less than that of chromium steel R2.

Fig. 67 shows the appearance of samples of steel 30Kh and chromium-plated steel 20 after oxidation resistance tests in contact with V_2O_5. The dark spots on the chromium-plated samples are sections with an oxide film which did not crumble; the light surface is the bright dense layer of metallic chromium.

Fig. 68 shows the cross section of a sample of chromium-plated steel 20 which has undergone oxidation-resistance tests in contact with V_2O_5. It is to be seen from the figure that the chromium layer has been preserved almost in its entirety.

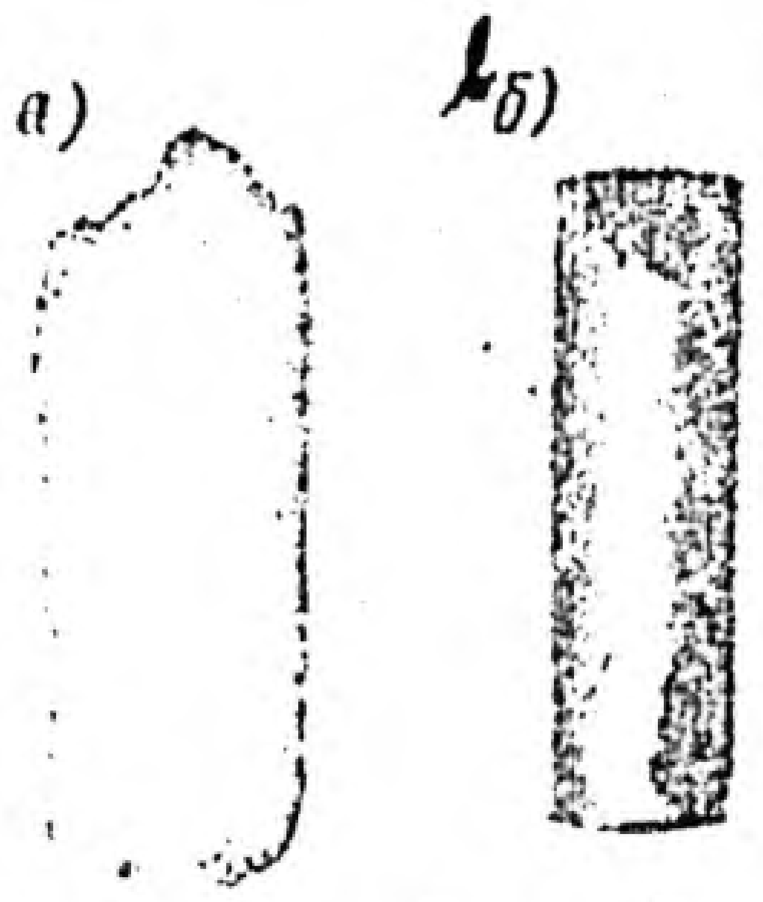


Fig. 67: Samples after oxidation resistance test in contact with V_2O_5 at 700°; test period 550 hours [15]:

a - steel 30Kh;
b - chromium-plated steel 20.

Fig. 68. Cross section of sample of chromium-plated steel after oxidation resistance test in contact with V_2O_5 at 700°; test period 550 hours. Magnification 596 X [15].

Oxidation-resistant electrolytic chromium coatings are employed both as independent coatingsand as two-layer and multilayer coatings in combination with nickel or other metals. Two-layer chromium coatings with nickel are employed in mechanical engineering to protect steel parts, as well as parts of other metals, particularly molybdenum, against oxidation.

Chromium and molybdenum have similar thermal expansion coefficients; hence an interlayer of chromium ensures good adhesion between molybdenum and a surface layer of nickel.

The technological process of depositing chromium and nickel on molybdenum consists of the following basic operations:

(1) pickling in a mixture of sulfuric and phosphoric acid (1:1);

(2) chromium plating at a current density of 120 a/dm^2 and electrolyte temperature of 85°, layer thickness 25 μ ;

(3) pickling in a 50% solution of hydrochloric acid;

(4) nickel plating in an electrolyte having the following composition:

$NiSO_4 \cdot 7\ H_2O$	350 g/l
$NiCl_2 \cdot 6\ H_2O$	60 g/l
H_3BO_3	30 g/l
pH of electrolyte	2.5
current density	2-5 a/dm^2
electrolyte temperature	50°
Thickness of nickel layer	175 μ

A two-layer chromium-nickel coating such as this protects molybdenum against oxidation at 1100° for 300-400 hours [80].

Chromium and chromium-nickel coatings also ensure a high thermal stability for molybdenum. Thus, molybdenum with a single-layer chromium coating 70-100 μ thick withstands more than 100 thermal cyclings from 1200-1300° to 200° and more than 250 thermal cyclings from 1000-1100° to 200°.

Electrolytic chromium and chromium-nickel coatings have been employed to protect steel and molybdenum parts of gas turbines (nozzle blades, combustion chambers, etc.) against oxidation, and for the sleeves of plug connectors and other parts subjected to the action of elevated temperatures.

The basic disadvantage of electrolytic chromium and chromium-nickel coatings is their brittleness and tension.

Diffusion Chromium Coatings

Chromizing represents a process of saturation of the surface of steel or cast iron with chromium. A high surface hardness and resistivity to wear, as well as increase in the corrosion resistance and oxidation resistance of steel and c cast iron parts, are hereby achieved.

Chromizing is carried out in solid, gaseous, and liquid media, and also in a vacuum*.

The phase composition and properties of the chromized layer depend on the carbon content of the steel. In the chromizing of low-carbon steel there is formed a solid solution of chromium in the alpha iron. The chromized layer of medium and high-carbon steel consists predominantly of the chromium carbides Cr_7C_3 and $Cr_{23}C_6$, which impart a high hardness to the article.

The values of the microhardness of the diffusion layer of chromium versus the carbon content of the metal to be chromized are given in Table 57.

Table 57

Microhardness Of Diffusion Layer Of Chromium [19]

1 Хромируемый металл	2 Содержание углерода %	3 Микротвердость, кГ/мм²	
		4 диффузионного слоя	5 основного металла
6 Железо	0,05	257	148
7 Сталь 10	0,10	645	161
8 Сталь 45	0,50	925	191
9 Сталь 30ХГСА	0,35	1265	218
10 Сталь У10	1,07	1450	175
11 Чугун	3,50	1920	137

1 - Chromized metal; 2 - Carbon content, %; 3 - Microhardness, kG/mm²; 4 - of diffusion layer; 5 - of base metal; 6 - Iron; 7 - Steel 10; 8 - Steel 45; 9 - Steel 30KhGSA; 10 - Steel U10; 11 - Cast iron.

The thickness of the diffusion layer of chromium depends on the temperature and the duration of the chromizing process (Table 58 and Fig. 69). The thickness of the diffusion layer of chromium which is the most often employed is 0.1-0.2 mm.

The maximum concentration of chromium in the diffusion layer is observed on the surface of the coated metal (Fig. 70).

The operating temperature for parts with a diffusion chromium coating ranges from 800 to 900° [11, 19, 61, and others].

The complex saturation of parts with two or more elements ensures oxidation resistance for the parts at higher temperatures. Thus, chromium aluminizing increases the oxidation resistance of steel articles up to 1100°, and that of articles of nickel based alloys up to 1200° [30, 82].

A description of the technological process of chromizing by the first three methods is given in the metallographic and reference literature [11, 23, 25, 30, 55, 61, etc].

The vacuum method of chromizing is discussed in detail in the work by N. S. Gorbunov [19].

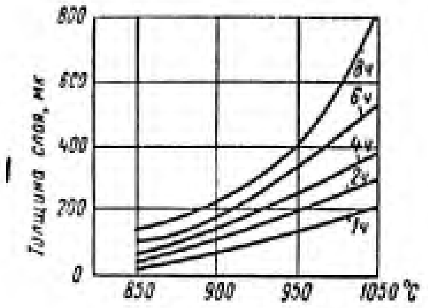


Fig. 69. Thickness of diffusion layer of chromium versus chromizing temperature [19]:
1 - Layer thickness, μ

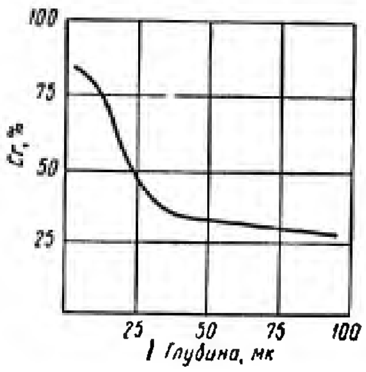


Fig. 70. Chromium content of diffusion layer at varying depths [19]:
1 - Depth, μ

Use is also made of diffusion saturation of steel with chromium and silicon; chromium, aluminum, and silicon; and other elements.

The use of chromium diffusion coatings for protection against oxidation is particularly effective for steels of brands E1402, E1417, and E1437, the oxidation resistance of which after chromizing is increased respectively fifteen, twelve, and fourfold [11].

Table 58

Thickness Of Diffusion Layer Of Chromium On Iron Versus Chromizing Conditions [19]

1 Время, ч	2 Толщина слоя хрома (мк) при температуре			
	850°	900°	950°	1050°
1	31	85	115	200
2	44	109	214	273
4	76	138	—	359
6	90	163	308	486
8	123	206	361	764

1 - Time, hours; 2 - Thickness of chromium layer (μ) at a temperature of.

In the chromizing of stainless steels the surface of the latter is enriched with chromium up to 30-60%; at the same time, the steels become insensitive to intercrystalline corrosion.

The effectiveness of chromium diffusion coatings in increasing the oxidation resistance of stainless steels is manifested particularly under conditions of direct contact between the steel and vanadium pentoxide at elevated temperatures.

Fig. 71 shows the oxidation kinetics of stainless steel E1417 with various thermodiffusion coatings in contact with an artificial ash containing 10% vanadium pentoxide. The curve of oxidation of an electrolytic chromium coating tested under the same conditions is given for the sake of comparison. It is to be seen from the figure that diffusion chromium coatings and the siliconized layer are characterized by high resistance. The best results were exhibited by the electrolytic chromium coating.

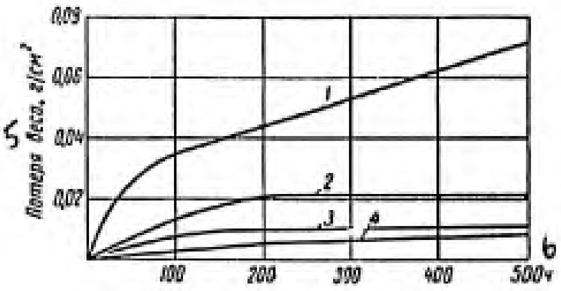


Fig. 71. Kinetics of oxidation of steel E1417 with various coatings in contact with an artificial ash containing 10% V_2O_5 at 730° in an atmosphere of air + 0.3% SO_2 + 6% H_2O [12]:
1 - Calorized layer;
2 - Chromium diffusion coating;
3 - Siliconized layer;
4 - Electrolytic chromium coating;
5 - Weight loss, g/cm²;
6 - Hours.

Non-ferrous metals (nickel, cobalt) and their alloys may also be subjected to chromizing [82]. Their resistivity to oxidation at high temperatures is hereby greatly increased.

Before being chromized, copper and its alloys are coated with a layer of nickel, since chromium does not diffuse into copper.

Of late, industry has employed chromizing to protect parts of molybdenum and its alloys (blades of gas turbines and other parts) against oxidation.

The basic disadvantages of chromizing are deformation of the parts, the impossibility of preserving the exact dimensions due to conduct of the process at high temperatures, and the technological complexity of chromizing large-sized parts.

These disadvantages can be eliminated by application of heating of parts by high-frequency currents in chromizing [21].

The advantages of the method are reduction of the time consumed by heating of parts; heating to a high temperature of the surface layer of the metal only, without change in the structure and properties of its basic mass; and the possibility of machining individual sections of the surface of a part, as well as articles of great length (pipes, strips, wire), the rate of formation of the diffusion layer of chromium in this case being several hundred times greater than in the case of heating in furnaces; the period of formation of a diffusion coating 0.2 mm thick is 8-15 seconds.

Chromizing has been industrially applied for protection of the following parts against oxidation: the mufflers and exhaust pipes of diesel engines, molds for the manufacture of glass articles, the pipes of heat exchangers, valve tappets, burner nozzles, spark electrodes of ignition furnaces, punching dies, the parts of gas turbines and gas furnaces, and in many other instances for combating the oxidation of parts.

2. NICKEL, NICKEL-CHROMIUM (Ni -- Cr). AND NICKEL-PHOSPHORUS (Ni -- P) COATINGS

Nickel coatings have not been widely applied as oxidation-resistant coatings in industry. The use is well known of nickel coatings in the glass industry for the rollers of annealing furnaces which come in contact with hot glass; for valves in steel nitriding plants; for coating the parts of various instruments operated at elevated temperatures in aggressive media; etc.

As is known, electrolytic nickel is characterized by high purity, for which reason it offers far better resistance to oxidation at high temperatures than does metallurgical nickel. In particular, it is stable in water vapor up to 600° [83].

Electrolytic nickel-chromium coatings (7-9% Ni, the balance chromium) are characterized by relatively high oxidation resistance. These coatings are deposited from an electrolyte containing 250-270 g/l of chromium anhydride and 75-100 g/l of nickel sulfide, at a current density of 35-50 a/dm^2 and temperature of 55-60°. The minimum layer thickness for protection of steel against scale formation is 40 μ [15].

Nickel-chromium coatings have displayed good resistivity to destruction in protracted tests (4000hours) in a gaseous mixture containing sulfur dioxide and carbon dioxide, and superheated steam at 650° and in an atmosphere of air at 750°. After tests under the conditions indicated there was formed on the nickel-chromium coating a brown-colored oxide film which protected the coating from further oxidation. Under the film there was a bright layer of the metal of the coating. There was virtually no weight gain in samples with a nickel-chromium coating, as may be seen from the following data:

Test period, hours	500	1000	4000
Weight gain of samples, $g/dm^2 \cdot h$	0.00004	0.00008	0.00007

Ni-Cr coatings are recommended for protection against corrosion of parts operating at temperatures of 600-700° [15] and 900° [84].

Nickel-phosphorus coatings, deposited electrolytically or by chemical means and known under the designation of chemical nickel, have become widely used in industry in recent years. The coatings contain 7-11% P, the balance being Ni.

The nickel-phosphorus coatings are deposited from solutions of varying composition; the solutions shown in Table 59 have been the most widely used.

Nickel-phosphorus coatings are characterized by high hardness. Immediately after the coatings have been deposited, their hardness equals 55-57 HRC, and after heat treatment at 400° and holding for one hour, the hardness rises to 67 HRC. The wear resistance of nickel-phosphorus coatings is not inferior to that of electrolytic chromium coatings, and the coefficient of friction over steel and cast iron is approximately 30% lower than with chromium.

Nickel-phosphorus coatings are oxidation-resistant up to 650° in an atmosphere of air and superheated steam. The layer thickness in this case must range from 30 to 50 μ. Figures 72 and 73 show curves of oxidation of pearlitic steel with no coating and with a nickel-phosphorus coating 50 μ thick at 650° in air and in superheated steam.

The oxidation resistance of nickel-phosphorus coatings is considerably lowered in the presence of carbon dioxide and sulfur dioxide.

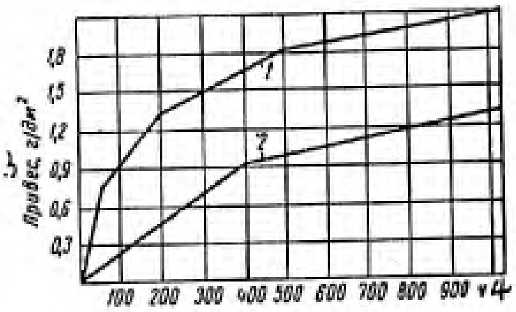


Fig. 72. Kinetic curves of oxidation of samples of steel 15KhMFKR with no coating at 650° [59]:
1 - in steam atmosphere;
2 - in atmosphere of air;
3 - weight gain, g/dm²;
4 - hours.

Nickel-phosphorus coatings have been employed abroad to protect pistons of an aluminum alloy from burning through under the action of fuel combustion products containing lead.

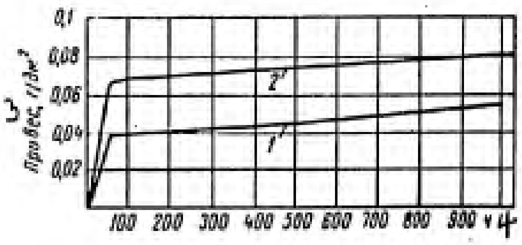


Fig. 73. Kinetic curves of oxidation at 650° of samples of steel 15KhMFKR coated with chemical nickel [59]:
1 - in steam atmosphere;
2 - in atmosphere of air;
3 - weight gain, g/dm²;
4 - hours.

3. ALUMINUM, NICKEL-ALUMINUM (Ni -- Al), AND ZINC-ALUMINUM (Zn -- Al) COATINGS

Aluminum coatings on steel and cast iron articles are formed through saturation of the surface of the latter with aluminum. This process is termed calorizing.

Several calorizing methods have been developed, of which the following have come to be the most widely used in industry: (a) calorizing in powdered mixtures; (b) liquid calorizing; and (c) metallizing with aluminum followed by homogenizing.

In calorizing in powdered mixtures, parts are placed in containers or retorts, covered with calorizing compound, and heated for a certain period while access of air is prevented. The calorizing mixture consists of aluminum or ferro-aluminum powder, which is the source of saturation with aluminum, and ammonium chloride (NH_4Cl). To prevent sintering or fusing of the aluminum powder, a powder of aluminum oxide (alumina) or kaolin is sometimes added to the calorizing mixture.

Liquid calorizing is carried out in baths with melted aluminum and iron added in the form of iron chips.

Table 59

Composition of Solutions And Conditions Of Depositing Nickel-Phosphorus Coatings [11, 14, 15, 59, 91]

1 Состав раствора и режим осаждения покрытия	2 Рецептура растворов						
	№ 1	№ 2	№ 3	№ 4	№ 5*	№ 6	№ 7**
3 Никель сернокислый, г/л	—	30	140	—	—	—	—
4 Никель хлористый, г/л	30	—	—	21	21—22	30	30
5 Натрий сернокислый, г/л	—	—	80	—	—	—	—
6 Натрий лимоннокислый, г/л	—	—	—	—	25—47	—	10
7 Цитрат натрия, г/л	—	—	—	—	—	100	—
8 Натрий хлористый, г/л	—	—	20	—	—	—	—
9 Натрий уксуснокислый, г/л	10	10	—	10	—	—	—
10 Гипофосфит натрия, г/л	10—12	10	8—10	24	23—24	10	10
11 Кислота борная, г/л	—	—	20	—	—	—	—
12 Водный раствор аммиака, мл/л (25-процентный)	—	—	—	—	50—55	—	—
13 Аммоний хлористый, г/л	—	—	—	—	—	50	—
14 Плотность тока, а/дм²	—	—	1—2	—	—	—	—
15 pH раствора	8—9	4,3—5,0	2—3	4,8—5,3	—	8—10	4—6
16 Температура раствора, °C	90	92—95	70	90—92	85—92	83—90	83—90
17 Скорость осаждения, мк/ч	6	5—6	—	—	17—19	5	—
18 Характер раствора	19 Кислый	19 Кислый	19 Кислый	19 Кислый	20 Щелочной	20 Щелочной	19 Кислый

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21 * Для покрытия деталей из алюминиевых сплавов.
22 ** Для покрытия деталей из пластмасс и стекла.

1 - composition of solution and conditions of depositing coating; 2 - solution formula; 3 - nickel sulfate, g/l; 4 - nickel chloride, g/l; 5 - sodium sulfate, g/l; 6 - sodium citrate, g/l; 7 - sodium citrate, g/l; 8 - sodium chloride, g/l; 9 - sodium acetate, g/l; 10 - sodium hypophosphite; 11 - boric acid, g/l; 12 - aqeous ammonia solution, ml/l (25%); 13 - ammonium chloride, g/l; 14 - current density, a/dm²; 15 - pH of solution; 16 - temperature of solution, °C; 17 - deposit rate, μ/h; 18 - nature of solution; 19 - acid; 20 - alkaline; 21 - for coating parts of aluminum alloys; 22 - for coating parts of plastics and glass.

In calorizing by the metallization method, the sprayed material, aluminum wire, is melted by the gas flame or electric arc method and deposited under pressure on the surface of the part treated. The calorized articles are subjected to subsequent high-temperature annealing for formation of a diffusion layer, lowering the brittleness, and equalizing the composition of the surface layer.

The calorizing compound, conditions of calorizing by the three methods, and basic data on the aluminum coating are given in Table 60.

Chiefly, parts of iron and low-carbon steel are subjected to calorizing. Parts of low-carbon steel and gray cast iron are less often calorized.

The structure of the calorized layer consists of a solid solution of aluminum in alpha iron and intermetallic compounds of the $FeAl_3$ type.

Calorized parts are characterized by high oxidation resistance, owing to the formation on their surface of a film of the aluminum oxide Al_2O_3, which is stable toward the action of high temperatures.

In the surface layer of calorized steel, the concentration of aluminum reaches 40-50%, while to ensure oxidation resistance it is sufficient to have 10-15% Al in the surface layer.

The resistance of calorized parts to scale formation is six to ten times greater than that of non-calorized parts [20, 23].

Shown in Fig. 74 is a diagram which characterizes the relative service life of parts of the producer-gas plants of a tractor and automobile at temperatures which in places reach as high as 1000-1050°. The parts indicated in the diagram were in service 4000 and 5000 hours before complete wear-out, and non-calorized parts no longer than 100-400 hours. The calorized throats and chambers of producer-gas driven automobiles were in service 2665 hours before general overhaul, and non-calorized ones 300-500 hours [19].

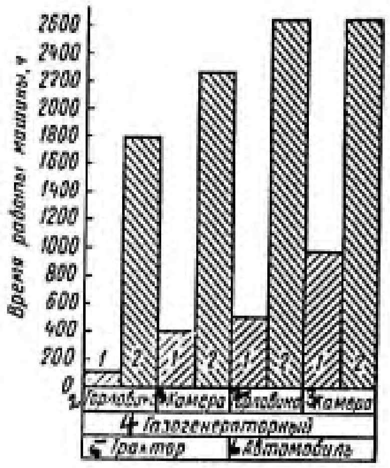


Fig. 74. Results of comparative tests of calorized (2) and non-calorized (1) parts of producer-gas plants [20]:
1 - operating period of vehicle, hours;
2 - throat;
3 - chamber;
4 - producer-gas driven;
5 - tractor;
6 - automobile.

The effectiveness of calorizing steel molds for precision casting is illustrated in Table 61.

Thus, the oxidation resistance of calorized molds of steel of brand 2 is twice as high as that of molds of oxidation-resistant stainless steel and eight to nine times as high as that of non-calorized carbon steel [19].

It is recommended that calorized steels be employed at operating temperatures no higher than 900° [61].

The aluminum coatings obtained by various calorizing methods have proved themselves to be good oxidation-resistant coatings and have been widely used in industry for protection of a wide variety of parts of machinery and mechanisms against oxidation: pipes for steam boilers, parts of producer-gas driven tractors and automobiles (gasification chamber, throat, grating, ring), locomotive parts, grate bars, furnace fittings, collector pipes, parts of piston engines, nozzles of jet engines, turbine blades, tools for casting non-ferrous metals, flasks for precision casting, carburizing pots, containers, crucibles for fused salts, etc.

Table 60

Conditions Of Calorizing By Various Methods And Characteristics Of Aluminum Coatings [11, 23, 72]

1 Метод алитирования	5 Алитирующий состав, % (весовые)	11 Режим алитирования		14 Режим диффузионного отжига		15 Глубина алитированного слоя, мм	16 Глубина слоя после отжига, мм	17 Концентрация алюминия в поверхностном слое, %	18 Твердость алитированного слоя по Виккерсу HV
		12 температура °C	13 продолжительность, ч	12 температура °C	15 продолжительность ч				
2 В порошкообразной смеси	6 1) Ферроалюминий 60 Окись алюминия 39—39,5 Аммоний хлористый 0,5—1 7 2) Ферроалюминий 99—99,5 Аммоний хлористый 0,5—1 8 3) Алюминий 50 Окись алюминия 49—49,5 Аммоний хлористый 0,5—1	950—1100	4—12	950—1100	5—6 3—4	0,1—1	—	40—50	400—500
3 Жидкостное алитирование	9 Ванна с расплавленным алюминием и железом: Алюминий 92—94 Железо 6—8	700—800	1	900—1000	4—5	0,2—0,3	0,45	50	500
4 Металлизация с последующим диффузионным отжигом	10 Алюминиевая проволока марки А3, диаметр проволоки 0,6—1,5 мм Напыление алюминия производится электро- или газовым аппаратом	19 24—30 в, давление 6 ат, расстояние до обрабатываемой детали 100 мм		900—950	1,5—2	0,3—0,5	0,5—0,7	—	400—42
				1200—1250	20—40 20 мин	0,3—0,5	0,9—1,0	—	—

1 - calorizing method; 2 - in powdered mixture; 3 - liquid calorizing; 4 - metallization with subsequent homogenizing; 5 - calorizing compound, % (by weight); 6 - ferroaluminum 60; aluminum oxide 39-39.5; ammonium chloride 0.5-1; 7 - ferroaluminum 99-99.5; ammonium chloride 0.5-1; 8 - aluminum 50; aluminum oxide 39-49.5; ammonium chloride 0.5-1; 9 - bath with melted aluminum and iron: aluminum 92-94; iron 6-8; 10 - aluminum wire of brand 3, wire diameter 0.6-1.5 mm; aluminum sprayed with electric or gas equipment; 11 - calorizing conditions; 12 - temperature, °C; 13 - period, hours; 14 - homogenizing conditions; 15 - depth of calorized layer, mm; 16 - depth of layer after homogenizing, mm; 17 - concentration of aluminum in surface layer, %; 18 - Vickers hardness of calor-

ized layer, HV; 19 - 24-30 v; pressure 6 atm; distance to calorized part 100 mm; 20 - minutes.

Table 61

Comparative Data On Stability Of Steel Molds For Precision Casting 20

Material of molds	Operating temperature, °C	Stability toward scale formation, hours	Condition of surface of molds
Carbon steel	900-950	No longer than 75	Surface completely oxidized
Oxidation-resistant chromium-nickel steel	900-950	300-350	Oxidized less than carbon steel, but cracked and became unfit for further use
Steel 20, only externally calorized (0.5-0.8 mm)	900-950	No less than 600-700	After 500 h operation, subjected to recalorizing, whereby oxidation resistance of molds is increased another 350-400 hours

Aluminum coatings may also be utilized for local protection of steel articles against carburization during carburizing [75].

The use of metallization coatings consisting of the compositions metal plus metal oxide, metal plus nitride, metal plus carbide, and other compounds has become known of late for protection against oxidation.

Most often use is made of Al + Al_2O_3 and Al + SiO_2. These coatings are deposited with conventional electric metallization equipment, with the difference that the powder of the metal oxide, carbide, or other compound is fed through the nozzle together with the compressed air; an air suspension is hereby formed.

The advantages of this form of coating are high density and oxidation resistance. In addition, the necessity of carrying out subsequent homogenizing disappears. Such combined coatings are recommended for the burner liners of the combustion chambers of gas turbine installations, furnace heads, and other parts subjected to high temperatures.

In engineering abroad, use is made of an oxidation-resistant nickel-aluminum coating obtained by electrodeposition of nickel from a chloride sulfate bath followed by electrodeposition of aluminum under one of the following sets of conditions:

(1) from a melt of salts of KCl • NaCl and $3NaF \cdot AlF_3$, at a temperature of 700° and current density of 2-15 a/dm²;

(2) from a melt of salts of NaCl and Al Cl_3 at a temperature of 160° followed by fusion by heating in air for several hours to 500-600°. The aluminum is hereby diffused into the nickel layer to form a nickel-aluminum alloy.

The Ni -- Al coatings (25-43% Al) obtained by this method, 50 μ thick, display a high resistivity to oxidation in air at 550°, but at 1000° their protective properties decrease because of diffusion of the ironinto the coating.

The oxidation resistance of nickel-aluminum coatings in an atmosphere of air is approximately 10 times as great as that of nickel coatings (Fig. 75) [85].

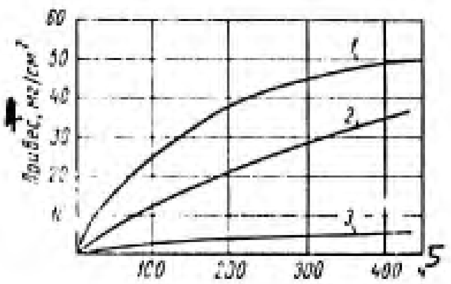


Fig. 75. Curves of oxidation of nickel and nickel-aluminum coatings at 1000° [85]:
1 - nickel coating;
2 - nickel-aluminum coating, 8 μ thick;
3 - nickel-aluminum coating 25 μ thick;
4 - weight gain, mg/cm²;
5 - hours.

Of the oxidation-resistant combined aluminum coatings, interest is presented by a two-layer zinc-aluminum coating (75 μ Zn + 75 μ Al), deposited layer by layer by the spray metallization method.

4. SILICONIZED LAYER

A siliconized layer is formed as a result of saturation of the surface of steel and cast iron with silicon.

Along with high corrosion and wear resistance, a siliconized layer is characterized by good oxidation resistance.

The gas method of siliconizing is employed in industry; in it the parts to be treated are placed in a hermetically sealed retort and covered with ferrosilicon or silicon carbide (SiC); chlorine, which interacts with the ferrosilicon (or carborundum) to form silicon tetrachloride ($SiCl_4$), is passed through the retort, which is heated to 950-1050°.

When the gaseous silicon tetrachloride comes in contact with iron, free silicon is liberated in accordance with the reaction

$$3\ SiCl_4 \div 4\ FeCl_3 + 3\ Si.$$

The atomic silicon which is formed diffuses into the steel. The depth of the siliconized layer at 1000° and with holding for 2-4 hours is 0.5-1.0 mm.

The microstructure of the siliconized layer represents a solid solution of silicon in alpha iron. The silicon concentration in the surface layer reaches 14%. The hardness of the siliconized layer amounts to 250-300 HB. The siliconized layer is brittle and does not lend itself readily to machining by cutting tools. It is stable in sea water and in nitric, sulfuric, and hydrochloric acids at room and elevated (80-100°)

temperatures. It resists wear in aggressive media well.

The oxidation resistance of the siliconized layer, according to the data in various bibliographic sources, falls within the 800-900° range [61, 62, 72]. Siliconizing also increases the oxidation resistance of such metals as molybdenum, niobium, and tungsten.

Siliconizing for the purpose of increasing oxidation resistance and protecting against gas corrosion is employed for the friction parts of automobile and tractor engines: valves, pistons, etc.

Good results in protection against wear and oxidation are yielded by the recently developed process of complex saturation of the surface of steel articles with chromium and silicon, known under the designation of chrome-siliconizing.

B. NON-METALLIC COATINGS

5. CERAMIC COATINGS

Ceramic coatings are designed chiefly for protection of metal articles from oxidation, general and intercrystalline corrosion, erosion, and wear at high temperatures. Such coatings are simultaneously electric and thermal insulating coatings, as well as being stable toward the action of fused metals.

The use of ceramic coatings makes it possible to economize considerable quantities of costly high-alloy alloys. For instance, the utilization of ceramic coatings in England to protect the combustion chambers of jet engines reduces the consumption of high-alloy chromium-nickel alloys by 65%.

The oxides of the metals aluminum, beryllium, magnesium, chromium, silicon, zinc, titanium, manganese, zirconium, nickel, cobalt, iron, calcium, etc., serve as the basic material for ceramic coatings. For the formation of oxidation-resistant special-purpose hard ceramic coatings use is made of the carbides, borides, and silicates mullite ($3Al_2O_3 \cdot 2SiO_2$), forsterite (Mg_2SiO_4), spinel ($MgO \cdot Al_2O_3$), and zircon ($ZrSiO_4$).

The influence of the various oxides on the oxidation rate of iron is shown in Table 62.

The value of the linear expansion coefficient of certain oxides is given in Table 63. As may be seen from this table, with the oxides of group II, the value of the linear expansion coefficient is the same as with the iron of chromium and chromium-nickel steels.

The basic technical requirements set for ceramic coatings are given in Table 64.

The two most widespread methods known at the present time for applying ceramic coatings are flame spraying of refractory oxides and various metals in the form of powders or rods and the method of pulverization of slip or immersion in slip (for coatings designated as oxidation-resistant enamels).

Table 62

Influence Of Various Oxides On The Rate Of Gas Corrosion Of Iron [18]

Oxide Group	Oxides	Influence on oxidation rate of iron
I	TiO_2, Cr_2O_3, Fe_2O_3, NiO, ZnO, B_2O_3, Al_2O_3, CuO, SiO_2	Reduce oxidation rate
II	PbO, Na_2O, MgO, CaO, BaO	Increase oxidation rate
III	ZrO_2, MnO	Have no effect on oxidation rate

Table 63

Linear Expansion Coefficient Of Certain Oxides [18]

Oxide Group	Oxides	Linear expansion coefficient	$\frac{\alpha_{ox}}{\alpha_{Fe}}$
I	ZnO, B_2O_3, Al_2O_3, SiO_2	$1 \cdot 10^{-6}$ — $7 \cdot 10^{-6}$	0.10-0.37
II	Na_2O, MgO, CaO	$1 \cdot 10^{-5}$ — $2 \cdot 10^{-5}$	1.0-1.05
—	Oxides of iron and chromium and chromium-nickel steels	$1 \cdot 10^{-5}$ — $1.9 \cdot 10^{-5}$	—

The composition and properties of certain ceramic coatings applied by flame spraying are given in Table 65.

Coatings of the Rockide type, widely advertised by American firms, are applied by flame spraying of rods of sintered aluminum or zirconium oxides.

For application of the AR-58 coatings, as well as coatings based on zirconium dioxide, the rods are produced from a doughy compound consisting of calcined powder of aluminum or zirconium oxides and water glass. The pressed rods are subjected to drying at a temperature of 200±10° for one hour.

For better adhesion these coatings are applied to a metal sublayer sprayed from wire Kh20N80T, Kh20N80T3, 1Kh18N9T, or E1435, as well as nickel or molybdenum wire; the thickness of the sublayer is 0.2-0.3 mm. The thickness of the coatings applied by flame spraying falls within the 0.12-2.5 mm range.

Table 64

Technical Requirements Set For Ceramic Coatings [18]

Technical requirements	Method of applying coating
Protection against oxidation at high temperatures of articles of metals, alloys, and other materials	Introduction into coating of maximum amount of the oxides TiO_2, Cr_2O_3, ZnO, B_2O_3, Al_2O_3, SiO_2, etc., which increase the oxidation resistance of iron, and a minimum amount of the oxides PbO, Na_2O, CaO, MgO, BaO, which lower the oxidation resistance of iron
Fusion (sintering) of coating at annealing temperature and solid state at operating temperatures	Addition to slip(suspension) of an oxidation-resistant filler, chiefly Al_2O_3 (6-8%)
High adhesion to material of article	Addition to frit composition of the oxides CaO (1-2%) and NiO (0.5-1%), which possess good solubility in the lower layer of the scale of iron (FeO)
Closeness of linear expansion coefficients of coating and material of article	Addition of Na_2O (around 15%) and P_2O_5 (2-2.5%)

The composition of the ceramic coatings applied by the pulverization method with subsequent high-temperature roasting is shown in Table 66.

The composition of the charge is selected so as to ensure the necessary physical and mechanical and chemical properties for the ceramic coatings. For instance, the oxides Al_2O_3, Cr_2O_3, TiO_2, B_2O_3, etc., foster increase in the oxidation resistance of coatings but possess a linear expansion coefficient far smaller than that of steel. This disadvantage is compensated by the addition of oxides such as Na_2O, MgO, CaO, and others.

Ceramic coatings with additions of compounds containing lithium have of late come into wide use [89, 90].

Additions containing lithium lower the roasting temperature of ceramic coatings by 65-120°. The possibility is hereby created of introducing into the composition of the coatings high-refractory compounds such as boron nitride, etc., as a result of which the heat resistance, hardness, and mechanical strength of the coatings are increased.

Ceramic coatings containing lithium have a thermal expansion coefficient near that of steel; this predetermines their high thermal stability.

Table 65

Composition And Properties Of Certain Ceramic Coatings Applied By The Flame Spray Method

Composition and properties	Coatings			
	Rockide A	Rockide Z	Rockide Zs	AR-58
Basic components, % (by weight)	Al_2O_3--98.6	ZrO_2--98.0	ZrO_2--65 SiO_2--34	Synthetic corundum of brand AS-320--77;heat-resistant sodium glass (modulus 2.9-3.0)--23
Knoop hardness*	2000	750	---	Microhardness 2000 kg/mm^2
Porosity, %	8-12	8-12	8-12	---
Melting point,°C	1960	2460	1650	---
Maximum operating temperature, °C	1650	2300	----	2000-2500 for brief periods
Density, g/cm^3	3.6	5.7	3.8	----
Linear expansion coefficient	$7.3 \cdot 10^{-6}$ (30-1480°)	$9.6 \cdot 10^{-6}$ (30-960°)	$4.1 \cdot 10^{-6}$	----
Thermal conductivity at 1000°, cal/cm · sec · degree	0.014	0.005	0.005	----
Rate of spraying of layer, cm^2/h	1000 to a depth of 0.25 mm	----	450 to a depth of 0.25 mm	-----

*The Knoop hardness is determined at a load of the order of 1 kg with a diamond-shaped Knoop hardness indenter. The indenter is a diamond pyramid with a rhombohedral base of which the obtuse angle is 172° 30′ and the angle between the ribs and the short diagonal of the base 130°. The length of the indentation is seven times greater than the width.

The Knoop hardness is defined as the ratio of load P to the square of the major diagonal of unreduced indentation d^2:

$$H = 12.87 \frac{P}{d^2} \text{ kG/mm}^2.$$

The hardness of thin coatings and parts of brittle materials (glass, enamel) may be measured by this method [88].

Owing to the good fluxing and wetting capacity of compounds containing lithium, very thin (13-25μ) and dense ceramic coatings are obtained which possess good adhesion with the basic metal.

The technological process of producing heat-resistant enamel coatings includes (1) preparation of the surface of the parts; (2) preparation of the frit; (3) preparation of the slip; (4) coating of the parts.

For preparation of the frit the charge is composed of the oxides of various metals, and the oxides are melted at 1400-1500° for 1-1.5 hours. The melt is granulated in cold water.

The slip of heat-resistant enamel is obtained by mixing the ground frit with additions of refractory oxides or other compounds, Chasov Yar clay, and water. The entire mixture is ground in a ball mill and passed through a screen with 6000-10,000 openings per square centimeter. The viscosity of the slip must fall within the 14-17 sec range. Before the slip is applied, the surface of the parts is subjected to pickling, water and sandblasting, or metal grit treatment. The slip of the enamel is applied by the pulverization method by means of a paint sprayer with a small nozzle (KR-11 M, O-37, etc.) or by immersion.

The layer of slip is first dried in air at 18-25° for 30 minutes, and then in drying cabinets at 110-150° for 20-30 minutes.

The enamels are roasted at 1050-1220° (depending on the composition of the heat-resistant enamels) for 5-8 minutes with subsequent air cooling.

The enamel coating must be unbroken, bright, of even thickness, and have no burnt-through spots. The thickness of the coating is 30-60 μ.

Enamels A-20, No. 7, and No. 10 (Table 66) are designed for protection of Armco iron and unalloyed steels against oxidation up to 800-870° without sharp temperature fluctuations.

Enamels A-417, A-418, No. 108, EV-55, and No. 12 are utilized to coat chromium-nickel steels and the alloy inconel.

Besides giving protection against oxidation, the enamels listed dependably protect chromium-nickel steels against intercrystalline corrosion, thereby ensuring preservation of the mechanical strength of the metal while in service.

Enamel A-417 protects the alloy inconel against oxidation for 500 hours at up to 900°.

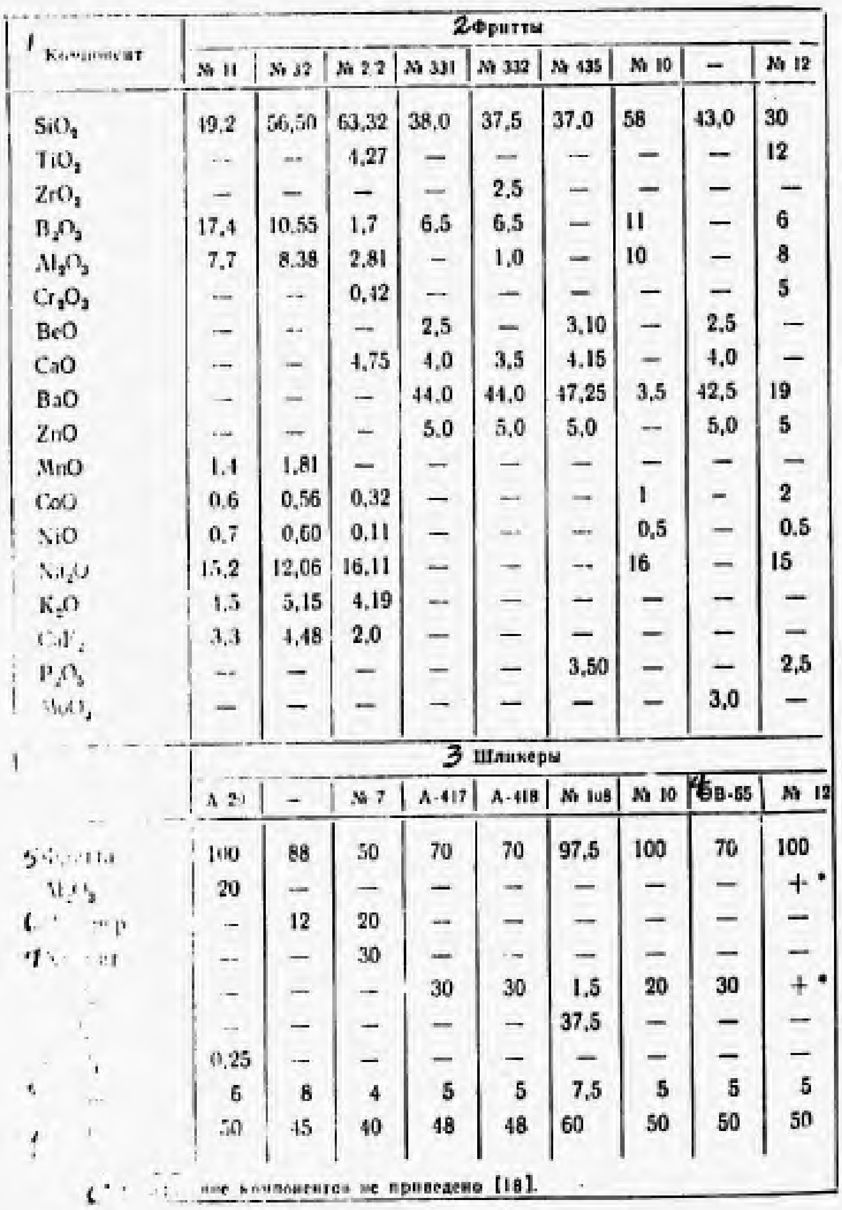
Enamel EV-55 is recommended for protecting high-temperature steels and alloys of brands E1435, E1437, E1617 employed under conditions of gas corrosion at temperatures of 1000-1100°. The service life of parts is hereby increased 2.5 to threefold.

Enamel No. 12 increases the oxidation resistance of steel Kh13N4G9 at up to 850-900° and is thermostable.

Enamel EZh-1000, consisting of frit, chromium oxide, Chasov Yar clay, and water, is characterized by a higher oxidation resistance. The composition of the frit includes quartz sand, boric acid, barium carbonate, calcium carbonate, titanium dioxide, and zinc oxide, mixed and melted at a temperature of 1350-1400°.

Table 66

Composition Of Certain Heat-Resistant Enamels (Parts Or % By Weight) [4]



1 Компонент	2 Фритты								
	№ 11	№ 32	№ 22	№ 331	№ 332	№ 435	№ 10	—	№ 12
SiO_2	49,2	56,50	63,32	38,0	37,5	37,0	58	43,0	30
TiO_2	—	—	4,27	—	—	—	—	—	12
ZrO_2	—	—	—	—	2,5	—	—	—	—
B_2O_3	17,4	10,55	1,7	6,5	6,5	—	11	—	6
Al_2O_3	7,7	8,38	2,81	—	1,0	—	10	—	8
Cr_2O_3	—	—	0,42	—	—	—	—	—	5
BeO	—	—	—	2,5	—	3,10	—	2,5	—
CaO	—	—	4,75	4,0	3,5	4,15	—	4,0	—
BaO	—	—	—	44,0	44,0	47,25	3,5	42,5	19
ZnO	—	—	—	5,0	5,0	5,0	—	5,0	5
MnO	1,4	1,81	—	—	—	—	—	—	—
CoO	0,6	0,56	0,32	—	—	—	1	—	2
NiO	0,7	0,60	0,11	—	—	—	0,5	—	0,5
Na_2O	15,2	12,06	16,11	—	—	—	16	—	15
K_2O	1,5	5,15	4,19	—	—	—	—	—	—
CaF_2	3,3	4,48	2,0	—	—	—	—	—	—
P_2O_5	—	—	—	—	—	3,50	—	—	2,5
MoO_3	—	—	—	—	—	—	—	3,0	—
	3 Шликеры								
	А 20	—	№ 7	А-417	А-418	№ 108	№ 10	4 ЭВ-55	№ 12
5 Фритта	100	88	50	70	70	97,5	100	70	100
Al_2O_3	20	—	—	—	—	—	—	—	+ *
6 [illegible]	—	12	20	—	—	—	—	—	—
7 [illegible]	—	—	30	—	—	—	—	—	—
[illegible]	—	—	—	30	30	1,5	20	30	+ *
[illegible]	—	—	—	—	—	37,5	—	—	—
[illegible]	0,25	—	—	—	—	—	—	—	—
8 [illegible]	6	8	4	5	5	7,5	5	5	5
9 [illegible]	50	45	40	48	48	60	50	50	50

* [illegible]ние компонентов не приведено [18].

1 - component; 2 - frits; 3 - slips; 4 - EV-55; 5 - frit; 6 - diaspore; 7 - chromite; 8 - clay; 9 - water; 10 - content of components not given [18].

Enamel EZh-1000 is recommended for protection against oxidation of chromium-nickel steels in service at temperatures of up to 1000°. This enamel also increases the thermostability of the steel in sharp temperature fluctuations (Table 67).

Oxidation-resistant alloys are also employed to protect parts of molybdenum, tungsten, titanium, aluminum alloys, cast iron, etc., against gas corrosion at high temperatures. Enamel

EV-83 is employed for protection of aluminum alloys at temperatures up to 350-450°.

Owing to the diversity of their properties: oxidation resistance and thermal stability; resistivity to corrosion, erosion, and wear; electric and thermal insulation; high reflecting capacity; stability toward the action of fused metals; etc., ceramic coatings have come to be widely used in various branches of industry. In particular, ceramic coatings are utilized for protection of the parts of gas ranges, mufflers, burners of industrial furnaces, annealing boxes, heat exchangers, superheated steam pipelines, insulating facings, exhaust pipes, combustion chambers, atomizers, nozzles, intake pipes of aircraft and other engines, rotors and blades of gas turbines, ingot molds, pouring ladles, crucibles, ladles, and other devices for smelting and pouring aluminum, furnace inductors, rollers of heating furnaces, tuyeres of blast furnaces; and for the protective covers of thermocouples, and other parts and devices operating at high temperatures.

Table 67

Thermal Stability Of Certain Chromium-Nickel Steels And Alloys

Material	Number of cycles before appearance of cracks in testing within the temperature range of:	
	1100-200°	900-200°
Steel E1417:		------
with no coating	8 -- 10	
coated with EZh-1000	17 -- 22	------
Alloy E1435:		
with no coating	----	490
coated with EZh-1000	----	1225
Burner liner samples:		
with no coating	----	330
coated with EZh-1000	----	580

6. METAL-CERAMIC COATINGS

Metal-ceramic coatings consist of a mixture of metals and oxides, carbides, silicides, borides, or nitrides.

The basic purpose of metal-ceramic coatings is protection of metal articles against oxidation at high temperatures, and increase in their erosion, corrosion, and wear resistance.

The technical requirements set for metal-ceramic coatings are from the standpoint of thermal expansion coefficient, adhesion, and technological parameters the same as with ceramic coatings.

The basic methods of applying metal-ceramic coatings are (a) pulverization of a suspension prepared in advance from a dispersed mixture of metal and ceramics (in water with polyvinyl alcohol in xylene, trichloroethylene, etc.) with subsequent roasting, and (b) flame spraying.

A list of the currently best known metal-ceramic coatings is given in Table 68.

A coating of a mixture of nickel and magnesium oxide is applied to the surface of parts preheated to 400°. This coating is stable toward the erosion action of hot gases and thermal shocks.

Molybdenum disilicide is employed chiefly for protection of parts of molybdenum against oxidation. Having a linear expansion coefficient close to that of molybdenum, a coating of $MoSi_2$ resists thermal shocks well. Molybdenum disilicide is stable toward the action of fused metals and hot aggressive gases.

Multilayer coatings of molybdenum and aluminum oxide dependably protect graphite articles against oxidation at high temperatures. They consist of three layers of molybdenum each 75 μ thick, alternating with three layers of aluminum oxide each 25 μ thick. In addition, a layer of chromium 125 μ thick is applied to the coating to ensure reflecting capacity.

To improve adhesion, a layer of silicone is applied to graphite articles before coating.

Metal-ceramic coatings based on chromium and nickel boride considerably increase the resistivity of metals to oxidation. These coatings are obtained by sintering finely divided ($< 10\ \mu$) powders of chromium and nickel boride taken in various ratios, in an atmosphere of hydrogen at 1450°. The cermets obtained are ground, mixed with an organic binder, and molded into rods. Use is made as an organic binder of plastic POV-30 (an alloy of 70 polyethylene and 30% polyisobutylene); 20 parts of POV-30 are taken to 80 parts of the powder. Other components as well may be added to the cermets in question.

The coating consisting of 95% of the cermet CrB-Ni (the ratio $\frac{CrB}{Ni} = \frac{50}{50}$) and 5% silicon possesses good protective properties [86].

Glass ceramic coatings applied by the pulverization method with subsequent roasting are effective from the standpoint of oxidation resistance. To obtain the coatings, an aqueous suspension is prepared from a mixture of powders of metal and glass. The coatings are roasted in a neutral atmosphere (nitrogen, argon) at 1200-1350°. Better protection against the oxidation of steel is ensured by a glass chromium coating consisting of 80-90% Cr and the balance glass slag. Such a coating protects steel from oxidation virtually up to 1000° and is characterized by high stability toward thermal and mechanical shocks [4].

Table 68

Metal-Ceramic Oxidation-Resistant Coatings [4, 11, 67]

Coating, composition	Method of application	Layer thickness, mm	Oxidation resistance	
			Duration, hours	Temperature °C
Ni MgO (66%)(33%)	flame spraying	0.3-0.7	Several minutes, longer period	To 2000 1500
$MoSi_2$ Si -- 36.9%	flame spraying	0.1-0.2	500	1315
Same with addition of boron	evaporation in vacuum	0.025-0.075	200 100 50	1370 1650 1850
Carbide W Co (92%)(8%)	flame spraying	0.050	500 rapid heating cycles	From 20 to 730
Lamellar coating on graphite Mo + Al_2O_3	flame spraying by layer	Total 0.75 Mo -- 0.075 Al_2O_3 -- 0.125 of each layer	40 sec Longer period	3000 2200
(CrB - Ni)+Si (95%) (5%)	flame spraying	---	reduces oxidation rate of cast iron 20-fold	900
Glass chromium coating Cr -- 80-90%; glass slag ---balance	pulverization with subsequent roasting	0.1-0.2	---	To 1000
Glass metal coating		0.1-0.2	0.1-0.2	900

A glass metal coating of the following composition (% by weight) is recommended for protection of cast iron against oxidation:

Metal binder

Ni	70	70-95 parts
Cr	20	
B	5	
Si	5	

Glass slag

SiO_2	28.6	30-5 parts
B_2O_3	4.9	
Al_2O_3	0.8	
Cr_2O_3	23	
CaO	2.7	
BaO	33.7	
ZnO	3.8	
MnO_2	1.9	
CoO	1.0	

The coatings are roasted at 1000-1100°.

7. THERMOSTABLE PAINT AND VARNISH COATINGS

The thermal stability of paint and varnish coatings is determined by their composition, that is, by the nature of the of the polymer, pigments, fillers, and other components, and also depends on the thickness and continuity of the film. The continuity of the film, in turn, depends on the rate of the thermo-chemical processes occurring as the film is heated, and on the degree of adhesion and magnitude of internal stresses. The latter arise in a film as it is formed as a result of the volumetric changes occurring on volatilization of the solvents, and also in consequence of the difference in the linear expansion coefficients of the coating and base metal in the process of operation of the parts.

In addition, paint and varnish films are subject to the effects of aging, as a result of which they lose their elasticity and crack. This is observed with particular clarity in thermal cyclings.

Thus, paint and varnish films may be utilized to protect metal articles from oxidation at relatively low temperatures (100-500°).

The relative stability of various paint and varnish films toward the action of elevated temperatures is shown n Fig. 76. It is to be seen that the weight loss of paint and varnish films based on silicon resins when heated to 250° for 20 hours is 8-10% (curves 4 and 5), that of those based on epoxy resins around 18% (curve 3), and that of films based on acrylic resin and ethylcellulose 50% (curves 1 and 2).

Approximate data on the thermal stability of the most widely used paint and varnish coatings based on various film formers are given in Table 69.

The highest thermal stability is that possessed by the enamels based on siloxane resins (enamel No. 9, KO-88, KO-84, K-1 and K-2). They withstand heating for 200 hours and more at a temperature of 250-500°.

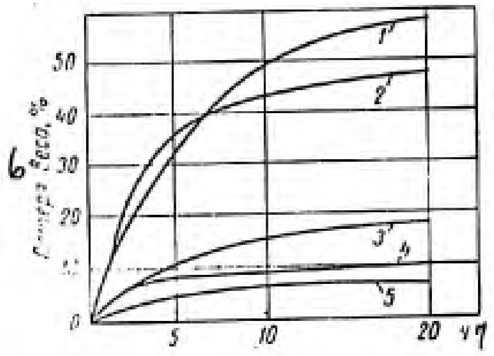


Fig. 76. Thermal stability of paint and varnish films at 250° based on 71 :
1 - ethylcellulose;
2 - copolymer of butylmethacrylate with acrylic resin;
3 - epoxy resin E-41;
4 - siloxane resin AK-47;
5 - siloxane resin F-9;
6 - weight loss, %;
7 - hours.

Table 69

Thermal Stability Of Certain Paint And Varnish Coatings (Holding Period 200 Hours) [42, 71]

Brand of enamel or varnish	Base of film-forms	Thermal Stability, °C
NTs-25 KhV, PKhV	Nitrocellulose Chlorinated polyvinyl chloride resin	80
EP colored GF, PF	Ethylcellulose Alkyd resins modified with semidrying oils	100 150
ALG-7 AL-701 PF-28	Alkyd resins modified with semidrying oils	200-300
ALG-14 FL-03 FL-76	Phenolic-oil resins	200
AG-10s AG-3a AS-82 AS-1sp	Acrylic resins	200
EP-09T E-5 E-11	Epoxy resins	230
VL-02 AO	Polyvinylbutyral resins	200--250
KO-84, K-2 of various colors No. 9, KO-88,K-1 K-3 yellow and green	Siloxane resins	250-300 450-550 400 250-350

However, the thermal resistance, that is, resistivity to the action of abrupt temperature changes, of these coatings is low (with the exception of K-3); in thermal cyclings with cooling to -50° the films crack.

Table 70

Systems Of Thermostable Paint And Varnish Coatings For Protection Of Parts Of Ferrous And Non-Ferrous Alloys [48, 71]

Steel or alloy	System				
	Operating temperature, °C	Priming	Coating	Number of coating layers	Total film thickness, μ
Carbon and low-alloy steels	300 -- long period; 350 - brief period	---	K-1;K-2; KO-84 of various colors	-----	------
Medium and high-alloy steels	above 400	---	Enamel No. 9; KO-88	-----	------ --
Aluminum alloys (anodized)	To 200	Al-701 of aluminum color	E-5, green; E-11, black; PF-28, black	3	35-55
	Above 250	K-1 of aluminum color K-2, yellow	K-2, green, black, brown, aluminum; KO-84, white and black	3	35-55
Magnesium alloys (oxide coated)	To 200-225	ALG-7; AG-10s	AL-701; E-5; E-11; A-0	3	80
	250-350	---	K-3, yellow and green	3	80

Enamels K-1, K-2, and KO-84 may also be employed in cold drying; in this case final hardening of the films occurswhile they are in service, when the parts are heated above 150-200°.

Alkyd, epoxy, and polyvinybutyral coatings are stabler toward the action of varying temperatures [71].

The paint and varnish and enamel films employed to protect parts of ferrous and non-ferrous metals are listed in Table 70.

Among the thermostable silicone coatings, use has been made of enamels based on varnish FG-9 (TU MKhP 2273-53), which adheres to metal well. The composition of the enamels is as follows:

Green:	FG-9, %	90-95
	Chromium dioxide, %	10-5
Apple Green:	FG-9, %	90-94
	Chromium dioxide, %	1-2
	Titanium, %	4-9

The enamels are applied to a parkerized steel surface with conventional air paint sprayers or in an electrostatic field. Drying is carried out at room temperature for 0.5-1 hour, and at a temperature of 150-200° for 1-2 hours. Final forming of the enamel film takes place after holding at room temperature for 24 hours.

The enamels are characterized by high adhesion to the base metal and by thermal stability up to 170-180°.

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