STRUCTURAL METAL MATERIALS

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ECONOMICAL STAINLESS NITROGEN STEELS: PROMISING SUBSTITUTES OF LIGHT ALLOYS

O. A. Bannykh[1]

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Main process and mechanical properties of corrosion-resistant steels with a structure of nitrogen martensite are considered. Advantages of such steels over light (aluminum, titanium) alloys with respect to specific static and cyclic strength, process ductility in hot and cold state, and fracture toughness are determined. It is possible to organize wide-scale production of semiproducts and articles from such steels at Russian plants of quality metal products.

The present work is devoted to a debatable topic. However, we presume that the data presented below give grounds for treating economical stainless martensitic steels alloyed with nitrogen as structural materials capable to replace light alloys. Specifically, these dada make it possible to compare the main characteristics of such widely used materials as steels with corresponding characteristics of light alloys, aluminum ones in particular. It is known that aluminum alloys begin to oust stainless steels from machine building, for example in the production of automobiles, railway cars, and aircraft and spacecraft parts.

Let us consider the main factors determining the expediency of the use of materials for this or that object (Table 1).

It will be shown below that we have enough reasons for placing a chromium-nitrogen steel of martensitic class among materials meeting all requirements presented in Table 1.

In principle, such steels can contain only chromium and nitrogen in addition to the elements required for deoxidation during melting (silicon and manganese). The latter elements are not scarce. The production of nitrided ferrochrome in Russia is developed enough. In order to shift the range of the brittle transformation to lower temperatures, it is sufficient to add to the composition of such steels 2 – 5% nickel and hundredths of percent of niobium, titanium or vanadium, which hinder grain growth in heating for hardening due to the formation nitrides stable until high temperatures.

[1] A. A. Baikov Institute for Metallurgy and Materials Science of the Russian Academy of Sciences, Moscow, Russia.

Undoubtedly, the production of steels in question is less harmful to ecology than the production of aluminum or titanium alloys.

TABLE 1. Main Factors Determining the Expediency of Use of Structural Materials

Technical and economical parameters of production of material or semiproduct:
1. Availability of burden materials.
2. Absence of harmful consequences for man and environment.
3. Energy intensity.
4. Cost.

Process properties in the production of parts:
1. Machinability (by cutting or pressing).
2. Weldability.

Mechanical properties of articles:
1. Strength (static and cyclic).
2. Ductility.
3. Fracture toughness (crack resistance).
4. Elasticity (toughness).

Operating properties of articles:
1. Endurance (service life).
2. Reliability (permissible possibility of damage).
3. Compatibility with other materials in a structure.
4. Compatibility with ambient media (corrosion resistance).
5. Specific qualities (density, electrical, magnetic, tribotechnical, and other properties).

Cost (at possible choice)

Capacity for recirculation

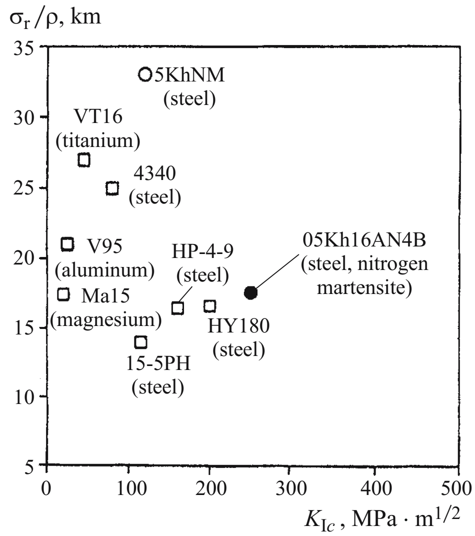

Fig. 1. Relation between specific strength and fracture toughness of steel 0Kh16AN4B with structure of nitrogen martensite and similar properties of high-strength alloys.

The lower energy intensity of the production of steels as compared to that of light alloys is another important circumstance. Melting of one ton steel from raw ore requires at most 2.5 – 3 thousand kW · h power; remelting of one ton steel in an electric furnace takes at most 500 kW · h. The production of one ton aluminum requires 12 – 14 thousand kW · h. This is very important, because virtually any process of power production is harmful for ecology. Suffice it to mention the greenhouse effect.

Comparative data on the power spent for fabrication of main structural materials are presented in Table 2. The table presents not only the amount of power required for making 1 m^3 material but also the consumption of power per unit parameter of strength and fracture toughness. It can be seen that plain carbon steels and traditional stainless steels are substantially superior to aluminum and titanium alloys with respect to the two latter parameters. The consumption of energy per unit volume for stainless steels and for aluminum alloys is close. However, we should not forget that the practical value of a structural material is commonly determined by the mass of the article produced rather than by its volume, and one cubic meter contains almost 3 times more stainless steel than aluminum alloy.

In the middle of the twenty first century the demand for iron ore will be minimized and determined only by the replenishment of metal losses to corrosion under the conditions of "saturation" of the industry with steel. The losses, which attain several million tons a year for today's steels produced at industrial scale, will be reduced. The necessity for "fighting" iron looses to corrosion should lead to considerable changes in the range of steels produced towards considerable growth in the proportion of alloy, primarily corrosion-resistant, steels in the world production.

This tendency is felt even today. The most vivid example is the marked growth in the production of stainless steels in the last ten years. In 1988 world producers have melted 13 mln tons stainless steels and in 1999 the figure exceeded 15 mln tons. The main producers of stainless steels are Japan (4 mln tons finished products), USA (2 mln tons), Germany, France, Italy, and South Korea (about 1 mln tons each). Unfortunately, Russia does not belong to leading producers of stainless steels at present. The explanation is simple, i.e., the long-term absence of Russian consumers of high-quality metal. However, domestic metallurgical works are capable of raising the production of stainless steels by many times using the available equipment and raw materials.

It should be noted that fabrication of steels with structure of nitrogen martensite does not require creation of special metallurgical equipment.

Such steels exhibit high process ductility in processes of hot and cold deformation. In hot rolling of these steels the reduction per pass can be 60 – 65%, and at room temperature it is possible to perform rolling with total reduction of 70 – 80% without intermediate annealing.

Acceleration of technical progress causes inevitable shortening of the life of machines, mechanisms, and struc-

TABLE 2. Power Spent for Production of Various Materials

Material	Consumption of power (F, GJ/m^3)	F/σ_r	F/K_{Ic}
Carbon steel	452	4.5 – 9.0	4.5 – 7.5
Stainless steel	855	3.9 – 12.2	4.2 – 5.7
Aluminum alloys	783	15.7 – 19.5	7.8 – 13.5
Titanium alloys	2542	18.2 – 36.0	16.9 – 25.4
Polyethylene	73	4.2	1.46
Wood	0.5	0.05	0.07

TABLE 3. Static and Fatigue Strength of Some Aluminum-Base, Titanium-Base, and Stainless Steels

Material		Density (ρ), $tons/m^3$	σ_r, MPa	σ_r/ρ, km	σ_{-1}, MPa (at $N = 2 \times 10^7$ cycles)	σ_{-1}/ρ, km
Al alloys	AK4-1	2.80	420	15.0	135	4.8
	D16T	2.87	450	15.6	150	5.4
	V95	2.85	520	18.2	165	5.8
Ti alloys	OT4	4.55	800	17.5	420	9.2
	VT6	4.45	900	20.0	550	11.8
	VT22	4.55	1100	24.2	550	12.0
Steels	30KhGSA	7.85	1100	14.0	600	7.7
	VNS-2	7.76	1250	16.0	620	8.0
	VNS-5	7.82	1420	18.5	720	9.2
	0Kh16AN4B	7.76	1600	20.6	770	9.9

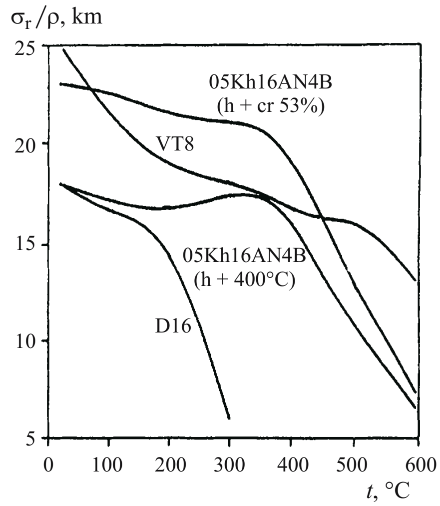

Fig. 2. Effect of testing temperature on the specific strength of steel 0Kh16AN4B, titanium-base alloy VT8, and aluminum-base alloy D16.

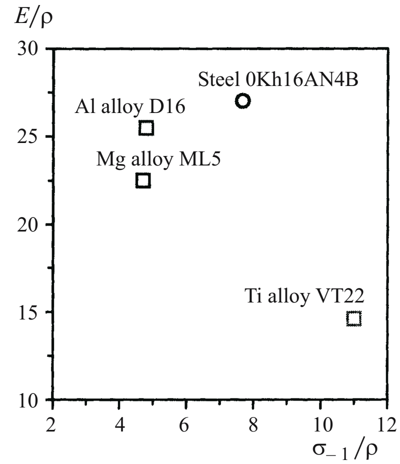

Fig. 3. Relation between specific fatigue resistance at 10^7 loading cycles and specific toughness for steel 0Kh16AN4B and light alloys based on Al, Mg, and Ti.

tures due to faster outdating. The automotive industry is a shining example.

In this connection, we should note that the capacity for iron-base alloys for recycling is quite high. This also concerns stainless steels alloyed with equilibrium amounts of nitrogen. In contrast to aluminum- and titanium-base alloys, the properties of which worsen considerably when they are reused, the properties after steels after second (and even repeated) use can be preserved at a level close to the properties of the original metal.

The most important operating characteristics of structural materials include the specific strength and specific stiffness (the strength-to-density ratio and the modulus of elasticity-to-density ratio, respectively). Steels with structure of nitrogen austenite are superior to other metallic alloys with respect to fracture toughness at an equal specific strength (Fig. 1, Table 3) and preserve a high specific strength up to 400 – 450°C (Fig. 2). Above about 500°C a high-strength titanium alloy has a somewhat better specific strength than the martensitic steel in question with 0.13% N.

However, this does not mean that titanium alloys can compete with such steels in many kinds of structure. This is demonstrated by Fig. 3, where we present the specific fatigue resistance (the ratio of the fatigue limit after 10,000 loading cycles to the density) and the specific stiffness (the modulus of elasticity divided by the density) of nitrogen steel 0Kh16AN4B bearing only 0.13% N and of some aluminum (D16), magnesium (ML5), and titanium alloys (VT22). The titanium alloy is somewhat superior to the steel where the fatigue resistance is concerned; however, with respect to the specific stiffness the alloy, which has a low modulus of elasticity, is substantially inferior to nitrogen steel 0Kh16AN4B.

It should also be noted that the tensile ductility of steel 0Kh16AN4B is much higher than that of light alloys (Fig. 4*a* and *b*). The absolute value of the fatigue limit (σ_{-1}) of steel

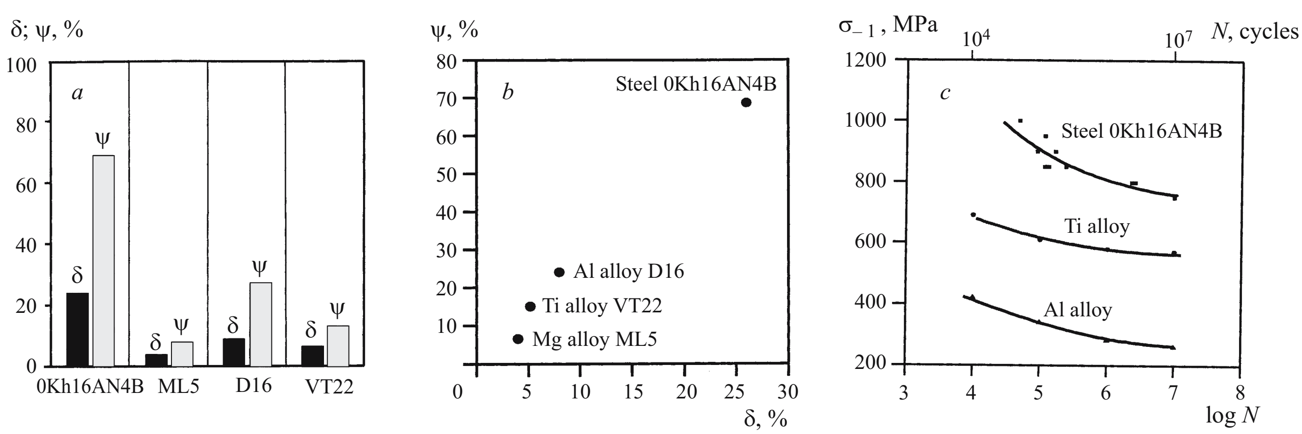

Fig. 4. Characteristics of ductility (*a*), their relationship (*b*), and fatigue resistance (*c*) of corrosion-resistant steel 0Kh16AN4B and light alloys (the data for the latter were taken from reference literature).

TABLE 4. Static and Cyclic Strength ($N = 5 \times 10^7$ cycles) of Some Steels and Aluminum Alloys in Air

Material	State	Strength		Fatigue resistance			
				in air		in water	
		σ_r, MPa	σ_r/ρ, km	σ_{-1}, MPa	σ_{-1}/ρ, km	σ_{-1}, MPa	σ_{-1}/ρ, km
Duralumin	Annealing	240	8.4	96	3.4	53	1.8
	Hardening	490	17.0	120	4.2	54	1.9
Silumin	Casting	200	6.9	60	2.1	—	—
Steel (0.1% C)	Hot rolling	430	5.5	230	2.9	130	1.7
Steel (0.2% C)	Casting	490	6.3	210	2.7	160	2.1
Steel 1Kh13	Hardening	630	8.1	390	5.0	270	3.5

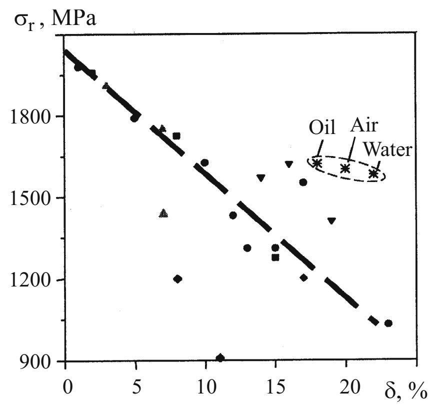

Fig. 5. Relation between ultimate rupture strength and elongation of high-strength stainless steels: ■) martensitic carbon; ●) martensitic precipitation-hardening; ▲) austenitic; ▼) austenitic precipitation-hardening; ◆) precipitation-hardened; ✳) martensitic nitrogen.

0Kh16AN4B is almost 3 times higher than that of the aluminum alloy (Fig. 4*c*).

An important property of steel 0Kh16AN4B is a low sensitivity of its mechanical properties to the cooling rate in hardening (Fig. 5).

It can be seen at the strength level ensured in steels of type 0Kh16AN4B by hardening in a wide range of cooling rates before tempering the ductility of these steels is much higher than that of steels of other types. The nature of the enhanced (for such level of strength) ductility of steel 0Kh16AN4B is explainable by its specific microstructure represented by lamellar nitrogen martensite with thin layers of retained austenite (10 – 15%), which are distributed relatively uniformly among the lamellas of martensite. The austenite layers permit plasticizing of the material during deformation.

TABLE 5. Corrosion Resistance of Steels in 3% Aqueous Solution of NaCl

Steel	Specific mass losses after 168-h testing, g/m^2	Corrosion rate, $g/(m^2 \cdot h)$
St 3	7.590	0.0450
AM	0.088	0.0005
12X18N9T	< 0.010	< 0.0001
AM/AM	0.115	0.0007
AM/09G2S	8.600	0.0512

Steel 0Kh16AN4B is well weldable by spot welding and by any kind of fusion welding; the electrode may be the same steel. The strength of welded junctions without heat treatment after welding is at least 75% of the strength of the base metal, and subsequent heat treatment ensures equal strengths of the welded joint and of the base metal.

The corrosion properties of chromium steels tested for cyclic strength can be compared with those of some aluminum alloys using the data of Table 4 (the tests have been performed by V. V. Romanov). This table presents static and cyclic strengths of carbon steels with 0.1 and 0.2% carbon and of chromium steel 1Kh13. The advantages of the stainless steel are obvious for testing both in air and in water.

In this connection, it can be expected that martensitic steels with structure of nitrogen martensite containing more chromium and having higher strength than steel 1Kh13 will have higher strength in water than steel 1Kh13.

Table 5 presents the corrosion resistance of steel St3, of martensitic nitrogen steel of the type considered (AM), and of stainless austenitic steel 12Kh18N9T in 3% solution of NaCl. It can be seen that the steel from the test heats, which has lower corrosion resistance than austenitic steel 12Kh18N9T, corrodes in the test medium about 100 times slower than carbon steel St3 or low-alloy steel 09G2S.

Welding virtually does not influence the parameters of corrosion resistance of stainless nitrogen martensitic steel AM. The ratio of the specific losses in the mass of specimens not subjected to welding and of welded specimens of type AM/AM is close to 1 (deviations from 1 on both sides do not exceed the range of natural scattering of the results).

The low corrosion resistance of welded specimens of “steel with structure of nitrogen martensite/steel 09G2S” is a result of the corrosion of the half of their surface belonging to steel 09G2S.

We used Erichsen extrusion (die) testing for evaluating the deformability of sheet material at room temperature

(GOST 1050–74). The thickness of the tested material was 1.2 and 2 mm. For comparison we also tested steel 09G2S.

The steel with structure of nitrogen martensite possessing a comparatively higher strength than steel 09G2S is not inferior to the latter with respect to the capacity to die forming, but the process requires application of a higher load (by 25 – 35%). The capacity of the martensitic nitrogen steel for die extrusion is little sensitive to the tempering conditions and is preserved at a high level after tempering at any temperature in a range of 600 – 750°C. A positive factor is a high stability of results in weldability tests of sheets 1.2 and 2.2 mm thick.

Returning to comparison of steels of type 0Kh16AN4B with steels less alloyed with chromium and with aluminum-base alloys we can note that the cost of sheets and bars from the former and from the latter is virtually the same and amounts today, by our data, to 60 – 80 thousand rubles per one ton semiproduct.

It is natural that the use of steel with structure of nitrogen martensite will not reduce abruptly the demand for light alloys. These alloys will always have a wide sphere of expedient applications.

Of course, the use of materials with strength higher than that of light alloys may require adaptation of the equipment of machine building plants to operation with them, which will be connected with some expenses and changes in many concepts and stereotypes customary for machine builders.