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ANALYSIS OF THE STEELS AND ALLOYS SELECTION WITH HIGH MECHANICAL PROPERTIES FOR MACHINE-BUILDING PARTS

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Abstract

According to the metallography terminology, steel is wrought alloy of iron with carbon (containing up to 2%) and other elements. This is one of the main metallic engineering materials. Wide application of steels in engineering is caused by combination of valuable complex of their mechanical, physical, chemical, and other properties.

The assortment of steels currently used in engineering is extremely wide. Developed informative marking system reflects the composition, production and treatment technology and the structure of different steel grades.

The range of carbon structural, building, carburized, spring, wear-resistant and corrosion-resistant steels is continuously improving.

Keywords: Wear-resistant steels structural, corrosion-resistant steels and alloys, heat resistant steel, high temperature steels and alloys, long-term strength, creep limit, superalloys.

1. Introduction

The production of high-strength steels used for manufacturing of critical parts in aircraft and rocket building is increasing. Range extension of operating temperatures in modern technology causes the necessity of finding new heat-resistant steels and alloys.

Operational characteristics of steel articles depend not only on chemical composition and phase ratio of components of steels, but also on quality of heat treatment. For the thermal treatment of steels polymer solutions, liquefied gases, molten salts and their solutions are increasingly used alongside with traditional technological media (water, oil).

Complex of operational characteristics of steel articles is determined by optimal (according to the criteria of working capacity as a part of machines) combination of composition and structure of steels.

Steels are mainly classified according to chemical composition and production method, reflecting the classification criteria of quality, as well as to structure, methods of shaping of steel articles and for the purposes intended.

According to chemical composition there are structural steels, which are subdivided into carbon, chromium, chromium-nickel, chrome-siliceous, etc.

According to the production method there are following types of steels.

A. Commercial quality steels are melted in open-hearth furnaces or converters. These steels contain up to 0.6% C, up to 0,06% S, and 0.07% P. Depending on the production method they are divided into killed (k), semi-killed (sk) and rimming (r) steels. Such a division is relative and it is associated with the method of degassing from the melt, the output of which is determined by the type of applied deoxidizer and smelting practice.

B. Qualitative steels are produced mainly in open-hearth furnaces with observance of high requirements to the composition of mixture of raw materials, technological modes of melting and casting. The content of sulfur and phosphorus in these steels should not exceed 0.035%. In steels of the same brand carbon content is permitted fluctuation of not more than 0.08%.

C. Steels of high quality are mainly produced in electric furnaces or in so-called acid open-hearth furnace. The content of sulfur and phosphorus does not exceed 0,025%. Fluctuation of carbon content in steel of the same brand does not exceed 0.07%.

D. Steels of extra quality are smelted in electric furnaces by using electroslag remelting or by other progressive methods of melting. The sulfur content is up to 0.015%. These steels are characterized by high impact strength, resistance to low temperatures and contact endurance.

2. Methods

Wear-resistant steels structural

One of the main the reasons of machines and mechanisms failure is wear of friction units, so increasing the service life of modern technologies is closely related to progress in the field of tribotechnical materials science.

A number of structural steels with high wear resistance has been developed, in which alloying additives are introduced or special processing methods are applied depending on the operating conditions.

The main criterion for the selection of steel for rolling bearings work surfaces of which are subject to multicycle contact loading with slip is high resistance to contact fatigue and abrasion. These requirements will be satisfied if the steel has high hardness, homogeneous structure, minimal content of non-metallic inclusions and metallurgical defects.

Typical representative of wear-resistant steel is ball bearing steel. According to the composition and structure ball-bearing steel belongs to the class of tool steels. Carbon content in them is about 1%. To increase the hardenability alloying elements are introduced into the steel (Cr, Si, Mn). The content of the element depends on the dimensions of the parts. For example, steel ШХ6 is used for parts with a maximal size to 10 mm and ШХ15ГС - for more than 30 mm, and large parts are made of steel 20Х2Н44. Heat treatment of ball bearing steels (hardening and low tempering) provides their hardness 60...66 HRC. For articles operating in hostile environments (sea water, weak solutions of acids and alkalis) corrosion-resistant high-carbon steel 95Х18 is applied. To stabilize sizes of bearings processing cold is used (-70 ° C).

Parts operated under the influence of shock loads are made of austenitic high manganese steel Г13Л. The shock loads causes surface cold hardening which provides reducing of wear resistance of conventional steels. After cold hardening wear resistance of the steel which have austenite structure increases. Such a structure is achieved by hardening at a temperature of 1000 ... 1100°C with air cooling.

Steel Г13Л is badly treated by cutting, so articles made of it are mainly obtained by forging or casting. It is applied for the manufacture of wear-resistant parts of crushing and milling equipment, dredges, excavators, chain tracks, arrows, etc.

Graphitized steel is used for manufacturing of parts used in sliding friction condition. It is obtained from high-carbon steel (1.5...2% C) with increased silicon content which promotes graphitization of cementite.

Graphitization is carried out by heating of cast or forged blanks to 840°C with soaking for 4 hours, it is followed by step cooling. Structure of graphitized steel is ferritic-cementite mixture with graphite inclusions. The latter plays role of lubricant which prevents seizing of friction surfaces.

Hardened graphitized steel (63 HRC) is used for manufacturing of drawing dies, trucks, etc.

To improve wear resistance of parts of machine intended for soil excavation, which are abraded by abrasive particles, coating of casting and surfacing materials are applied. Generally, they have high content (up to 4%) of carbide alloying elements.

Components of the structure of these materials are martensite, austenite, or their combinations. The quantitative ratio of austenite and martensite is regulated by adding of manganese and nickel into steel. Typical representatives of such hardening alloys are У25Х38, У30Х23Р2С2Г, У30Х26Н4С4Г (numbers after the letters У show the carbon content in tenths of a percent).

Corrosion-resistant steels and alloys

Corrosion-resistant category includes metallic materials resistant to prolonged exposure of corrosive media. Corrosion resistant steels are divided into two main classes: chromous which after air cooling have ferritic, martensitic, ferritic-martensitic, austenitic chromium-nickel, austenitic-ferritic and austenitic-martensitic structures.

Structure and properties of chromium steels depend on content of chromium and carbon in it. Upon contact of steel articles with oxidizing media chromium goes into a passive state forming on the articles surface oxide films or layers adsorbed oxygen. Steel with a chromium content of 12...14% acquires resistance to corrosion in air, water, seawater, in a number of acids, alkalis and salts. Hypoeutectoid steels 12X13 and 20X13 in annealed condition consist of chromium ferrite and pearlite, steel 30X13 is eutectoid with the structure of pearlite, 40X13 is hypereutectoid steel with the structure of pearlite + alloyed cementite + chromium carbides. Normalized steels 20X13, 30X13, 40X13 belong to martensitic class, and 20X13 - to semiferritic.

Chromium steels with structure of solid carbon solution in chromium have high corrosion resistance which is reduced during the formation of chromium carbides and increased after heat treatment and reduction of roughness of articles surface (grinding, polishing). Steels 3X13 and 4X13 are used for manufacturing of surgical instruments, X17 and X25T - for parts of equipment of chemical plants. Parts operating in highly aggressive environments (boiling nitric acid) are made of steels of ferritic class (X25T, X28). These steels are inclined to intercrystalline corrosion. Chromium-nickel steels alloyed with chromium and nickel (or manganese) have a higher resistance to corrosion in comparison with chromium. Steels of austenitic class (18% Cr, 9...10% Ni) are technological under pressure shaping, well welded, but have low casting properties and machinability. To obtain purely austenitic structure with high corrosion resistance nickel-chromium steels are heated up to 1110...1150°C (to dissolve the carbides) and hardened in water or in air. In case of violation of heat treatment regimes or operation of parts at higt temperatures (400...800°C) corrosion resistance of chromium-nickel steels reduces sharply as a result of intercrystalline corrosion. To eliminate this defect steels are additionally alloyed with titanium and niobium. These steels are called stabilized. Austenitic chromium-nickel steels 04X18H10, 08X18HЮ, 12X18H10T are used in aircraft manufacturing, shipbuilding and mechanical engineering.

Austenitic-ferritic chromium-nickel steels are characterized by lower content of deficit nickel, but have sufficiently high mechanical properties, resistance to corrosion and they are processable. Their disadvantage is instability of properties during fluctuations of chemical composition within the same grade.

Chromium-nickel steels of austenitic-martensitic class are referred to the number of high-strength materials. To improve mechanical properties they are hardened at 975°C (structure is unstable austenite and martensite) and are subjected to sub-zero treatment at -50...-75°C (about 50% of the austenite goes into martensite) and aging. After such a complex treatment steel parts acquire the structure austenite + tempered martensite.

To improve resistance to high temperature oxidation (chemical corrosion) chromium steels are alloyed with aluminum and silicon. The most common heat resistant steels are steels containing chromium and silicon (silchromes), chromium and aluminum (chromals), chromium, silicon and aluminum (silchromals). Typical representatives of heat-resistant steels are 40X9C2, 10X13CЮ, 12X18H9T.

Heat resistant steel and high temperature steels and alloys

High temperature steels or scale resistant include steels providing working capacity of articles at temperatures above 500°C for a predetermined time.

Heat resistance (scale resistance) is the ability of metal to resist chemical corrosion in dry gas medium at high temperatures. Iron forms oxides of three kinds - FeO, Fe_3O_4, Fe_2O_3. Below a temperature of 560-600C scale consists mainly of a dense layer of oxides Fe_2O_3 and Fe_3O_4. Layer of scale on the surface of the article hinders the diffusion of oxygen atoms to the metal. Below a temperature of 560-600C scale consists mainly of dense layer of oxides Fe_2O_3 and Fe_3O_4. Layer of scale on the article's surface makes it difficult for diffusion of oxygen atoms to metal. Above 600°C cracking of dense oxide film occurs and loose oxide FeO is formed which does not prevent access of oxygen to the metal surface. Heating to temperatures > 600°C leads to rapid oxidation of iron alloys, which is classified as chemical corrosion.

The main factor affecting on heat resistance of metal is structure and properties of oxide film. Table 1 shows comparative assessment of heat resistance of a number of metals, which is determined on a 5-point scale of oxidation rate in air medium at temperatures of 500 - 800°C.

It is seen that metals corresponding points 4 have good heat resistance due to the formation of dense oxide film with high protective properties on samples. For this reason, the chromium and aluminum along with silicon are used as alloying elements for heat resistance of steels improving. Oxides of these elements are not destroyed by heating. They have high density and high temperatures of melting and sublimation.

Due to the fact that aluminum and silicon promote brittle behavior of steels and make plasticity worse during pressure shaping, main alloying element in heat resistant steels is chromium. Steel containing 5% Cr (15X5) retains scale resistance to 600°C, 9% Cr (40X9C2) does to 800°C, 17% Cr (08X17T) does to 900°C.

For manufacturing of furnace equipment parts steels 20X23H18, 20X25H20C2 which have a temperature of scale resistance to 1100°C are used. These grades refer to austenitic class and are characterized not only by high heat resistance, but also by high level of high-temperature strength.

During the prolonged use of products under load lower than yield point and under heating to a temperature of about (0.4-0.5) T_m slow plastic deformation of metal occurs, which is called creep.

When creep occurs there are two opposite processes: strengthening by cold hardening and weakening as a result of recrystallization. If the second process is predominant, then processes that promote creep diffusion of carbon atoms, coagulation of phases recrystallization is developed in the sample.

Point	Metall	Assessment of heat resistance			Determinating factor
		quality	temperature range, °C	oxidation rate g / (m²h)	
1	Mg	Very bad	500-600	10^{-1}-10^{1}	Loose oxide film
2	Nb, Mo, W, Ti, Zr	Bad	700-800	10^{-1}-10^{3}	Destruction (degradation) of oxide film
3	Cu, Fe, Ni, Co	Satisfactory	500-600 700-800	10^{-3}-10^{-1} 10^{-1}-1,0	High defectiveness of relatively thick oxide film
4	Al, Zn, Sn, Pb, Cr, Be	Good	400-600 700-800	10^{-4}-10^{-3}	Dense oxide film
5	Ag, Au, Pt	Excellent	700-800	Lower than 10^{-6}	Low sensitivity to oxygen

3. Results and Discussion

High-temperature strength is property of material to resist deformation and failure at high temperatures. Criteria of high temperature of metal are creep limit and long-term strength.

Long-term strength is stress which leads to destruction of the sample at a predetermined temperature for a certain time corresponding to the conditions of products' use. Long-term strength is denoted as σ^{t}_{τ}, where the indices t and τ denote the temperature (°C) and testing time (h).

Creep limit is stress causing a predetermined amount of deformation of the sample during a certain time at a predetermined temperature. Creep limit is denoted as $\sigma^{t}_{\delta/\tau}$, where t is temperature, °C; δ - elongation,%; τ - time, h.

High temperature strength of metals is determined primarily by energy of interatomic bonds, which is characterized by physical constants of material - melting point, thermal expansion coefficient, thermal conductivity, etc. At the same temperatures of melting high temperature strength of metal depends on the temperature of their recrystallization.

Development of dislocation creep mechanism is prevented by alloying steels, formation of dispersed, carbide or intermetallic phases in them. The lower and more stable particles of these phases, the higher degree of strengthening of steel is. Alloying of solid solutions, which leads to increase of bond energy between atoms causes inhibition of processes of diffusion and growth of recrystallization temperature. In steels and nickel-based alloys the reinforcing effect is provided by primary carbides (TiC, VC, ZrC, NbC), secondary carbides ($Me_{23}S_6$, Me_6C, Me_7S_3) and intermetallic phases (Ni_3Ti, Ni_3Al, Ni_3Nb etc.). Steels and alloys with intermetallic phases have higher high temperature strength in comparison with carbide containing alloys.

Loaded parts of units with working medium temperature 450...470°C are made of chromium steels. To improve the performance characteristics, vanadium, tungsten, molybdenum, niobium, titanium is introduced into steel, which increase the temperature of recrystallization. These elements form carbides and Laves phases thereby increase high temperature strength of steel. Alloying with boron, zirconium, cerium and nitridation promote additional increase of high-temperature strength. To achieve optimal (by criteria of mechanical properties) high temperature strength, high-chromium steels 15Х11МФ and 1ХКВНМФ are hardened in oil at 1000...1060°C and tempered at 700...740°C. Structure of these steels after tempering is sorbitol or troostite.

Austenitic steels have a higher level of high temperature strength in comparison with pearlitic, martensitic, ferritic and martensitic-ferritic steels. They are characterized by a higher content of chromium and are alloyed with molybdenum, tungsten, vanadium, niobium and boron. Austenitic steels are plastic, well welded, but have poor machinability. To achieve high level of high temperature strength the following heat treatments are carried out: hardening at 1050...1200°C in water, oil and air and aging at 600...800°C.

Depending on the structure formed after heat treatment there are steels with carbide and intermetallic hardening. 4ХМН14В2М and 4Х15Н7Г7Ф2МС steels with carbide hardening are used for manufacturing of aircraft engine valves. Steels with carbide hardening are less strong than with intermetallic.

Articles made of so-called superalloys - nickel, cobalt, iron-nickel alloys withstand very high operating temperatures (up to 1000 - 1100°C or higher). They are used for manufacturing of critical parts of gas turbine engines, aerodynamic and industrial power plants. The first superalloys were developed in 1929, when British metallurgists Pilling and Bedford alloyed heat-resistant nickel-chromium alloy with small amounts of Ti and Al. Introduction of alloying elements has provided substantial increase of creep resistance. Research in this area helped to create a wide range of superalloys.

4. Conclusion

High temperature strength parameters of material are selected based on the guaranteed service life of machine or mechanism. It is often short enough.

Thus, recommended service life of a number of high-temperature constructions depending on the purpose is:

- For missiles and their power units - 1 hour;
- For power units of fighter aircraft - 100 hours;
- For civil aircraft power units - 1000 hours;

- For gas turbines of locomotives and ships - 10,000 hours;
- For gas turbines of stationary power units - 30,000 hours;
- For steam turbines for of stationary power units - 100,000 h.

According to the content of alloying elements heat-resistant steels and alloys are divided into low, medium and high alloyed steels. According to the structural features there are pearlitic, martensitic, austenitic steels, etc. There is a classification of steels based on their function.

For manufacturing of articles operated at temperatures of 350 ... 400 ° C steels 15, 20, 25, 30, 40 and 45 are used; for details of steam heaters, pipelines, turbines with operating temperature of 500...580°C - low carbon steels of pearlitic class alloyed with cobalt, molybdenum and vanadium (16M, 25XM, 12X1MФ).

After normalizing (950...1050°C) and tempering (650...750°C) high-temperature steels have lamellar pearlite structure.

At 950°C ХН55ВМКЮ alloy has strength $\sigma_{\text{В}} = 550$ MPa; $\sigma_{0,2} = 400$ MPa and long-term strength $\sigma^{950}_{100} > 140$ MPa and $\sigma^{950}_{100} > 65$ MPa. This alloy is used for manufacturing of gas turbine blades and other parts operating continuously under stress at temperatures to 950°C. It is seen that nickel-based superalloys which have complex chemical composition (10-12 components) are the most widespread alloy as heat resistant material.

Iron is usually presents in alloys as impurity, although some superalloys contain up to 30% of iron or more. Alloying with chromium (15 - 20%) provides alloy resistance to hot corrosion.

Molybdenum and tungsten being in solid solution or as a part of carbides increase heat resistance. Aluminum and titanium with nickel γ' form phase $Ni_3(Al, Ti)$ which is the primary strengthening phase. Cobalt is introduced into nickel alloys for intensification of precipitation hardening due to release of γ' - phase.

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