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Analysis Of The Effect Of Chromium Content On The Mechanical Properties Of White Cast Iron

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ABSTRACT

This article examines the effect of alloying elements of high chromium cast iron on the corrosion resistance and hardness of the alloy by heat treatment. Carbide formation and elongation strength limits were also analyzed depending on the amount of chromium and nickel.

KEYWORDS

High-chromium white iron, nickel, carbide, strength, alloy, heat treatment, corrosion resistance, hardness, microstructure.

INTRODUCTION

The high-chromium white irons have excellent abrasion resistance and are used effectively in slurry pumps, coal-grinding mills, shot-blasting equipment, and components for quarrying, hard-rock mining, and milling. In some applications they must also be able to withstand heavy impact loading. These alloyed white irons are recognized as providing the best combination of toughness and abrasion resistance attainable among the white cast irons.

In the high-chromium irons, as with most abrasion-resistant materials, there is a trade-off between wear resistance and toughness. By varying composition and heat treatment, these properties can be adjusted to meet the needs of most abrasive applications.

Specification ASTM A532 covers the compositions and hardnesses of two general classes of the high-chromium irons. The chromium-molybdenum irons (Class II of ASTM A532) contain 11 to 23% Cr and up to 3.5% Mo and can be supplied either as-cast with an austenitic or austenitic-martensitic matrix, or heat-treated with a martensitic matrix microstructure for maximum abrasion resistance and toughness. They are usually considered the hardest of all grades of white cast irons. Compared to the lower-alloy nickel-chromium white irons, the eutectic carbides are harder and can be heat-treated to achieve castings of higher hardness. Molybdenum, as well as nickel and copper when needed, is added to prevent pearlite and to ensure maximum hardness.

The high-chromium irons (class III of ASTM A532) represent the oldest grade of high-chromium irons. These general-purpose irons, also called 25% Cr and 28% Cr irons, contain 23 to 28% Cr with up to 1.5% Mo. To prevent pearlite and attain maximum hardness, molybdenum is added in all but the lightest-cast sections. Alloying with nickel and copper up to 1% is also practiced. Although the maximum attainable hardness is not as high as in the class II chromium-molybdenum white irons, these alloys are selected when resistance to corrosion is also desired.

Structure and types of white cast iron

All white cast irons are hypoeutectic alloys. Their typical microstructure on fast cooling from the liquid state consists of dendrites of transformed austenite (pearlite) in a white interdendritic network of cementite. Since white cast iron contains a relatively large amount of cementite as a continuous interdendritic network, it makes it hard and

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wear resistant but extremely brittle and difficult to machine. Completely white cast irons are limited in engineering applications due to this brittleness and lack of machinability. They are used where resistance to wear is most important and the service does not require ductility, such as liners for cement mixer and extrusion nozzles. A large quantity of white cast iron is used as a starting material for the manufacture of malleable cast iron. The range of mechanical properties for unalloyed white cast iron is as under.

MATERIALS AND METHODS

The main property of white wear-resistant cast irons is high wear resistance. White chromium cast irons surpass steel and gray cast irons in wear resistance by 4–12 times. However, to determine the possibility of their application in different conditions, it is important to know the characteristics of structural strength.

Mechanical processing and testing of specimens of white cast iron, especially martensitic, is difficult, and therefore there is relatively little data on the tensile strength of such cast irons. The data of the foundry department are given, which on samples cast in special sand molds, tested the tensile strength of white cast irons and obtained the following results. The tensile strength in tension of white pearlitic cast iron containing 1.5% Cr is 240-320 N/mm^2, nickel-chromium cast irons with carbides $(Fe, Cr)_3C$ in the cast state is about 220 N/mm^2, and tempered at 260° C - 350 N/mm^2.

The results of tensile tests of nihard (3.4% C, 2% Cr and 4% Ni) and high chromium cast iron (2.6% C and 26% Cr) are given in table 1.

The structure of white cast irons with a high chromium content consists of disconnected trigonal carbides $(Cr, Fe)_7C_3$. Therefore, cast irons of this type have a significantly higher toughness than low-alloyed white cast irons with carbides $(Fe, Cr)_3C$ forming a continuous carbide phase.

Table 1

Properties of white cast irons - nihard and high chromium

Cast iron	σ_B, N/mm^2	$\delta = \delta_{contr} + \delta_{pl}$,%	E,кN/mm^2	HB
Nihard	210–420	0,1–0,35	168–182	500–700
High chrome	595	0,2–0,4	220	450–650

Many researchers note that an increase in the carbon content at a constant chromium concentration causes deterioration of the mechanical properties, which professor associates it with an increase in the amount of the carbide phase in cast iron.

According to [1], in order to achieve the best mechanical properties of high-chromium (14–

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25% Cr) cast irons, one should adhere to their eutectic composition. In [2], it is recommended to use high-chromium cast irons (26% Cr) with a carbon content not higher than 2.6%, and cast iron with 12% Cr - from 3.5–3.7% C, since with an increase in the carbon content in the structure of cast irons large brittle needles of hypereutectic carbides appear, which sharply reduce the strength of cast irons.

The chromium content also affects the mechanical properties of white cast irons. In [1], the data of researchers are given that an increase in the chromium content to 5% reduces the strength of cast iron, at 12–15% Cr the strength reaches a maximum and then remains constant up to 27% Cr.

In [3], it is indicated that the retained austenite of the Klaymax alloy 42 cast iron matrix apparently increases the toughness of castings. Resarchers believe that hardening of the deposited metal such as steel X12 from high temperatures to the austenitic structure increases their resistance to shock loads.

We have studied the mechanical properties of a number of the most commonly used white cast irons, the chemical composition of which is given in Table 2, using a unified technique. The study of the tensile strength was carried out on specimens with a diameter of 18 mm, obtained by casting into rod molds without subsequent mechanical processing. The study of the ultimate strength in bending was carried out on samples with a diameter of 30 mm and a distance between the supports of 300 mm, cast into shell molds on pulverized bakelite.

As follows from the table 2, high-chromium cast irons ICh290X28N2, ICh260X17N3G3, ICh290X12M, ICh290X12G5, 15% Cr – Mo) with carbides of the type (Cr, Fe) $_7C_3$ have higher flexural strength and greater deflection than cast irons with cementite type carbides) and not alloyed type white cast iron. The tensile strength of high-chromium cast iron ICh290X12M and ICh290X12G3 is significantly (1.5 times) higher than that of IChX2N4 cast iron (nihard 2).

The flexural strength of white cast irons is the same as the best grades of modified gray cast iron with plate-shaped graphite. An increase in ultimate strength and deflection (by 15–25%) is observed during tempering.

Table 2

Mechanical properties of white cast irons under different heat treatment modes

Cast iron	Heat treatment	σ_n, N/mm²	f*, mm	σ_v, N/mm²
Pearlite white	Vacation 2 h at 200°C	$\frac{330}{280-380}$	$\frac{1,4}{1,1-1,6}$	-
Nihard - 2	Without heat treatment	$\frac{470}{400-480}$	$\frac{1,7}{1,6-1,8}$	-

	Vacation 3 hours at 230-250° C	$\frac{590}{550-610}$	$\frac{2,1}{2,0-2,15}$	266
	Hardening from 860-880 °C in air, tempering for 3 h at 230-250 °C	$\frac{490}{480-500}$	$\frac{1,7}{1,6-2,1}$	-
ICh290X28N2	Without heat treatment	$\frac{590}{570-610}$	$\frac{2,2}{2,1-2,3}$	-
	Vacation 2 hours at 560-580 °C	$\frac{610}{560-660}$	$\frac{2,0}{1,5-2,1}$	-
	Annealing at 880–900°C, quenching from 1100°C in air, tempering for 3 h at 520–560°C	$\frac{490}{460-530}$	$\frac{1,5}{1,4-1,6}$	-
ICh260X17N3G3	Without heat treatment	$\frac{550}{450-640}$	$\frac{2,1}{1,6-2,5}$	-
	Vacation 3 hours at 600-615 °C	$\frac{620}{580-660}$	$\frac{2,4}{2,3-2,5}$	-
	Double annealing at 860–880°C	$\frac{480}{470-490}$	$\frac{1,9}{1,8-2,1}$	-
Klaymax alloy – 42 (15 % Cr–Mo)	Hardening from 950 °C in air, tempering 2 h at 200 °C	$\frac{730}{610-880}$	$\frac{2,3}{1,9-2,6}$	-
ICh290X12M	Also	$\frac{740}{650-880}$	$\frac{2,3}{1,9-2,6}$	413,3

ICh290X12G5	Hardening from 820°C in air, tempering 2 h at 200°C	$\frac{700}{650-740}$	$\frac{2,25}{2,0-2,75}$	383

It is associated with stress relief due to low thermal conductivity of white cast irons, phase transformations associated with precipitation of dispersed carbides (ICh290X28N2, ICh260X17N3G3), intermediate transformation of austenite (IChX2N4, ICh260X17N3G3).

Note the good agreement between the results of our tests and the data on the tensile strength of nihard 2 cast iron.

The mechanical properties of commonly used grades of white iron are determined by the type, size, shape of primary and eutectic carbides to a much greater extent than by the characteristics of the metal base.

RESULT

Mechanical properties mainly depend on the type, quantity and size of carbides, which, in turn, are determined by the chemical composition of cast irons and the manufacturing technology of parts.

The type of carbides in the study was changed by alloying the base cast iron (2.7–3.1% C) with chromium from 5 to 31.1%. The amount of carbides in all cast irons was approximately the same: 26.6–32% and only in alloys with 29–31% Cr reached 35 wt. %. Mechanical properties were studied on cast samples after 2 h of tempering at 200 ° C.

The change in the mechanical properties of white cast irons with an increase in the chromium content is well explained by the change in the structure of these alloys. Mechanical properties are low until (5.07–7% Cr) (Fig. 1), while the carbide phase in the alloy crystallizes in the form of a continuous ledeburite skeleton. Beginning with 8.85% Cr, the mechanical properties are improved due to the appearance of large areas of isolated trigonal chromium carbides. The maximum strength in the investigated cast irons is observed when the carbide phase consists mainly of trigonal carbides of the M_7C_3 type, at 12–19% Cr.

These studies are in good agreement with the data of [4], which also noted an improvement in the mechanical properties of white cast irons, the carbide phase of which consists of isolated trigonal chromium carbides.

At a Cr content of 25% and higher, the fracture structure of the samples becomes rough and acicular.

The tendency to a decrease in the mechanical properties of cast irons with 3% C, containing more than 25% Cr, is apparently explained by a change in the type of carbides - the appearance of hypereutectic carbide needles and an increase in their number.

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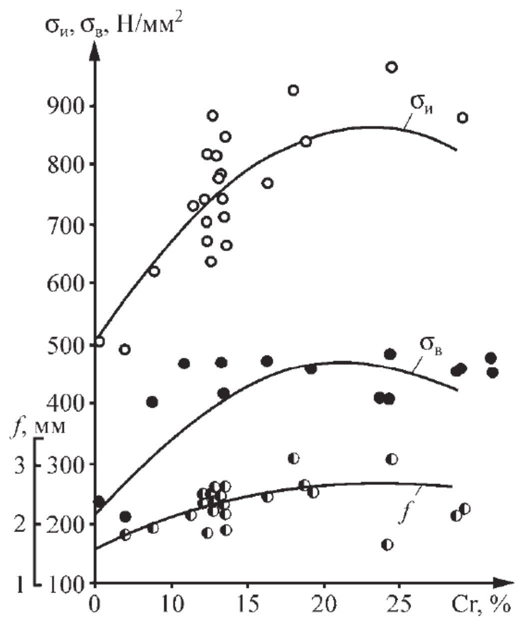

Figure 1. Effect of chromium content on mechanical properties of cast iron

The study of the effect of the structure of cast iron with trigonal chromium carbides on improving the mechanical properties of wear-resistant white cast irons led to the creation of a "eutectic" nihard (containing 7.5–15% Cr, 3–5% Ni) [5].

The amount of carbides changed as a result of an increase in the carbon content from 1.53 to 4.4% with a constant chromium content (12-14.8%). The effect of carbon content on mechanical properties was studied on cast samples after 2 h tempering at 200° C and after quenching in air and 2 h tempering at 200° C. Smelts with a low carbon content (up to 2%) were quenched at 950–980° C, and with a content of 2.5–4.2% C, at 900–930° C. Fig. 2 it follows that as the carbon content increases, the mechanical properties of cast irons decrease, which is associated with an increase in the amount of the brittle phase - carbides. This pattern is also noted in [6].

At a carbon content close to 3.5%, there is a sharp, abrupt decrease in tensile strength (Fig. 2). This phenomenon is associated with a change in the nature of the carbide phase - the appearance of large, brittle needles of hypereutectic carbides and, possibly, the presence of cementite.

In addition, at a content of 3.5% C, the nature of the fracture changes: from fine-grained and uniform - to coarse-needle.

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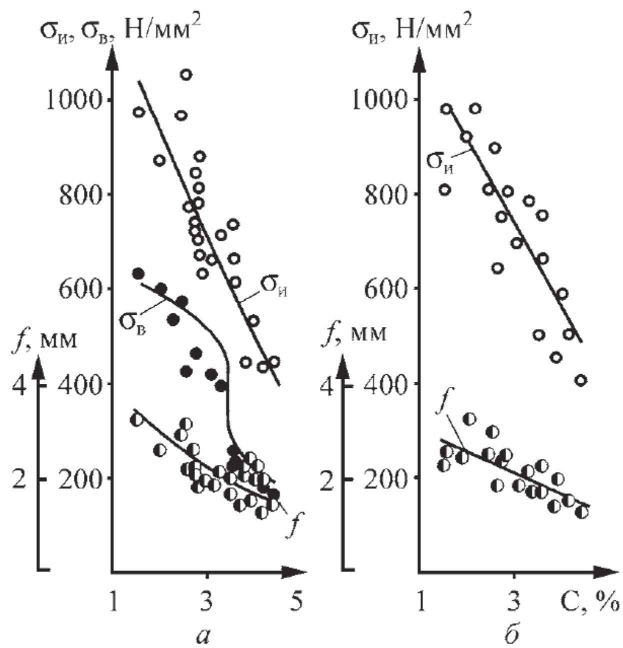

Figure 2. Effect of carbon content on mechanical properties of cast irons (12-14% Cr) after tempering at 200 ° C (a), quenching and tempering at 200 ° C (b)

A sharp drop in the mechanical properties of white cast irons with the appearance of hypereutectic carbides in their structure is also noted in [7]. Strength, as well as wear resistance, is more influenced by carbon content than chromium content (Fig. 3) [8]. Thus, an increase in the carbon content from 2.8% to 3.54% reduces the flexural strength (bend) by half, and an increase in the chromium content by 2.5 times (from 12.0 to 30.0%) - only by 1, 3 times, which is associated with the different influence of these elements on the change in the amount of carbides. A change in the content of carbon in chromium cast iron, for example by 0.7% (from 2.8 to 3.5%), increases the amount of carbides by 10%, and an increase in the chromium content by 18% (from 12 to 30%) in cast iron with 3% C increases the amount of carbides only by 3–5% .

Depending on the chromium content, the strength of cast irons decreases sharply at different carbon concentrations, in alloys with a higher chromium content - at lower carbon concentrations, which is caused by the formation of brittle large needles of hypereutectic carbides at a lower carbon content.

The sizes of carbides change as a result of different cooling rates of castings during crystallization. Different cooling rates were obtained using castings (sand or metal) of different thickness and shape with different thermal conductivity.

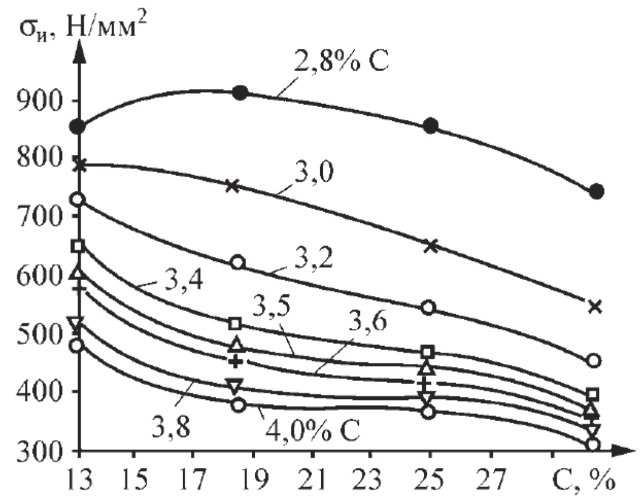

Figure 3. Comparative influence of chromium and carbon on the strength of white cast irons

Blanks for bending tests were cut from pre-annealed special cast blanks - plates and steps.

Then, samples 12 mm in diameter and 130 mm in length were made by turning, which were quenched in air from 930° C, and then tempered for 2 h at 200° C.

Fig. 4 it can be seen that with an increase in the size of carbides caused by a decrease in the cooling rate during crystallization, the ultimate strength in bending decreases.

Thus, with an increase in the size of carbides from 4–5 μm to 10–12 μm, the flexural strength of chromium cast iron (3% C, 12–14% Cr) decreases from 1230 N / mm2 to 310 N/mm^2, etc. 4 times. This reduction was obtained by comparing the strength of specimens from a 15 mm section cast into a metal mold and specimens cut from a 100 mm thick slab (100x400x400 mm) cast into a sand mold.

It is important to note that when this slab (100x400x400 mm) was cast into a metal mold, the flexural strength increased sharply and amounted to 980 N/mm^2, etc. was practically equal to the strength of thin-walled castings - a wedge with dimensions of 25x160x135 mm, cast in a sand mold.

The researchers have obtained convincing evidence of a large influence of the size of carbides not only on the wear resistance of chromium cast irons, but also on their strength. Hence the importance of using technologies that reduce the size of carbides, and, first of all, the use of technology for casting thick-walled parts into metal molds.

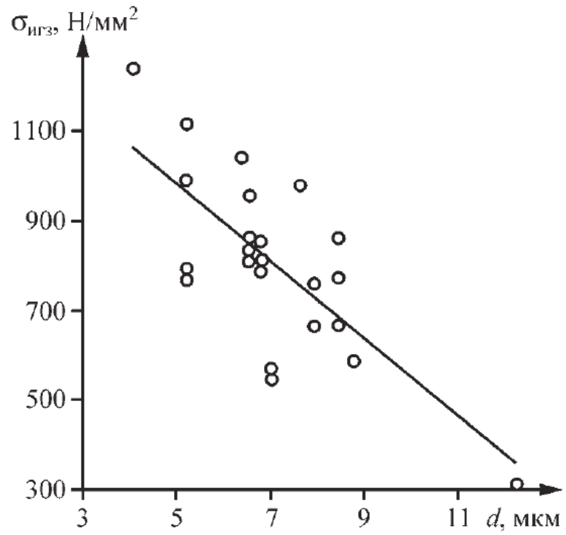

Figure 4. Influence of the value of carbides (d) on the strength of cast iron ICh290X12M

An increase in the strength, ductility, and toughness of wear-resistant alloys is possible with a change in the shape, size and relative position of the carbide component of the structure. This is confirmed by a sharp increase in the mechanical properties and, first of all, in the ductility of white vanadium cast irons with "spherical" carbides. The combination of "spherical" carbides and an austenitic matrix makes it possible to achieve such ductility of vanadium cast irons, which is difficult to obtain in cast irons with cementite or trigonal chromium carbides. From table 3 it can be seen that a number of vanadium cast irons have a large relative elongation (up to 8%).

Table 3

Mechanical properties of vanadium cast irons

C	Mn	V	$\sigma_в$ N/mm²	δ, %	HB
1,96	4,53	6,82	547	1,5	311
2,06	7,31	6,92	737	3,0	293
1,84	9,68	7,01	708	5,5	302
2,38	12,77	6,82	857	8,0	302
1,98	17,34	5,91	789	3,0	302

The relative elongation of white cast irons with trigonal chromium carbides is 0.2–0.4%. The high ductility of some cast irons is achieved by vanadium carbides and an austenitic matrix. However, to obtain high wear resistance, the use of a martensite matrix is much more effective than a stable austenitic one.

It is possible that these alloys will be effective at high shock loads. However, under conditions of abrasive wear with micro cutting, the wear resistance of such cast irons with a stable austenitic base (see Table 3) will be low.

The strength and ductility of carbide wear-resistant alloys is significantly increased by hot plastic deformation of castings - forging or rolling.

In [9], data are given on the hot working of nihard cast iron, after which the strength and toughness of the products are significantly improved. The microstructure of forged nihard consists of relatively isolated carbides, instead of a continuous ledeburite mesh in cast nihard.

In [9] data on a sharp increase in the ductility and strength of white cast iron containing,%: 2.4–3.2 C; 0.4-0.6 Si; 0.3-0.5 Mn; 0.1-1.5 Cr; 0.2-0.5 Ni; 0.2-0.6 V; 0.1–0.5 Mo, hot plastic deformation. Deformation at 850–1050° C led to the appearance of an elongation δ = 2.5% for specimens made of this cast iron, whereas in the cast state it was absent.

The literature contains scanty information about experimental work on hot deformation of castings from white iron and no data on the serial application of this technology.

Further work is needed to improve the strength and ductility of white wear-resistant cast irons by creating structures with smaller and more compact carbides. The use of alloying elements makes it possible to obtain compact carbides of the VC, TiC, etc. types in cast iron. The possibility of improving the structure of white cast irons gives the use of different methods of influencing the alloy during the crystallization period, in particular, the introduction of inoculators (suspension), modification.

CONSLUSION

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