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ANALYSIS OF SERVICE DURABILITY OF HIGH MANGANESE CAST STEELS UNDER ABRASIVE AND IMPACT-ABRASIVE WEAR CONDITIONS

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ABSTRACT

The paper deals with the study of the effect of high manganese steel alloying with nitrided ferrochrome on the abrasive and impact-abrasive wear resistance coefficients. Moreover, the structure formation of cast high manganese steel depending on the amount of entering nitride ferrochrome is examined. We assessed the effect of heat treatment on the wear resistance coefficients and the microstructure parameters of the test steel.

Cast Hadfield high manganese steel is the object of this study. The steel melt after alloying with nitrided ferrochrome in different amounts was poured into the moulds with different heat storage capacity. The samples obtained with different chromium contents as well as the samples crystallized at different cooling rates of the melt were investigated in accordance with the GOST method of assessing wear resistance under various conditions. In addition, we carried out metallographic investigations with modern analytical equipment. After the investigations, we determined the effect of alloying with nitrided ferrochrome on the abrasive and impact-abrasive wear resistance coefficients. During the study, we determined the chromium content in the composition of Hadfield steel at which it has the maximum abrasive and impact-abrasive wear resistance coefficients. Moreover, the effect of cooling rates of the melt in the mould on the value of these coefficients was assessed.

We considered the effect of alloying with chromium and cooling rates of the manganese steel melt in the mould on the change in the quantitative characteristics of the carbide phase. The effect of these factors on the austenite grain size and the anisotropy factor was determined. Also in the paper, we present the results of research of the effect of heat treatment on the chemical composition of the steel under study, microstructure parameters, particularly the austenite grain size and anisotropy. In addition, the paper presents the results of metallographic investigations of experimental sample surfaces obtained under the conditions of abrasive and impact-abrasive wear. In conclusion, we present general conclusions and recommendations on alloying high manganese steels with nitrided ferrochrome.

Keywords: high manganese steel, nitrogenous ferrochrome, abrasive and impact-abrasive wear resistance, alloying, chromium carbide, manganese carbide, austenite grain size, microstructure.

INTRODUCTION

Currently consumers of foundry products impose more and more strict requirements for its quality. In particular, this can be applied to the components operating under severe operational environments such as high temperatures, corrosive environments, abrasive and impact-abrasive wear, high contact loads. The alloys intended for the operation under such conditions are used for each group of the components.

High-manganese steel, in particular Hadfield steel is the most widespread among steels used as structural materials for the casts working under different types of wear conditions. However, it has long been used in industry, both domestic and foreign researchers have interest in it until this day.

The authors of works [1 - 3] have studied the effect of the chemical composition of Hadfield steel on such properties as the impact strength and toughness. They lined up a number of elements according to the reduction in the degree of the effect on these properties. In works [4 - 7], the effect of such alloying and modifying elements and complex additions as: titanium, calcium, vanadium, calcium and strontium carbonates, and the rare earth metals on the strength and plastic properties of high manganese steel, as well as its microstructure was explored. The positive effect of these elements on the designated parameters was mentioned. In works [5 - 7], the effect of the calcium strontium carbonate on the overcooling value was determined; this value reduces from 40 to 10 °C when introducing into the steel in an amount of 0.8 % of the weight of the metal that is processed. In this case, the carbide size reduces from 18 - 145 to 5 - 15 μm; the grain is disintegrated to 3 - 4 points; the impact toughness increases up to 40 %.

However, in these studies the effect of the chemical composition of steel on its main feature - wear resistance has not been studied.

The wear resistance of Hadfield steel is determined by many factors such as the chemical composition, heat generation of a cast in the mould (the melt cooling rate), the heat treatment mode, and others.

The work of the authors [8] deals with the study of the effect of alloying and deoxidizing complex with titanium, boron, calcium. They found that the use of this complex contributes to 20 % wear resistance coefficient increasing.

The thermal conditions for generation of a cast in the mould, specifically the cooling rate of the melt in the mould, have a significant effect on the wear resistance. A series of works [9 - 11] focus on the investigation of this effect. They reveal that the cooling rate of the melt in the mould affects the austenite grain size and the carbide phase parameters. Depending on the cooling rate, the abrasive wear resistance of this steel can vary by more than 20 %. Moreover, the authors of works [10 - 11] found that the cooling rate of the melt in the mould affects the stacking fault energy, the value of which identifies the steel hardening mechanism (deformation twinning or dislocation motion) under the influence of external loads. In addition, the authors of these works established the relationship between the stacking fault energy and abrasive wear resistance.

The works of foreign researchers [13 - 18] revealed that the elements that are added to the austenitic steels are divided into two types according to the degree of effect on the stacking fault energy: raising its value and lowering its value. Consequently, these elements have different effect on the wear resistance of high manganese steels.

When studying the wear resistance of Hadfield steel almost all scientific papers consider the abrasive wear processes. It should be noted that the elements made of this steel also operate under impact-abrasive wear conditions. In order to formulate adequate recommendations on applying this steel as a constructional material for operation under one or another conditions (abrasive or impact-abrasive wear) it is necessary to assess its wear resistance under various conditions, the effect of alloying with one or another element on this property together with the thermal conditions of cast forming in the mould.

EXPERIMENTAL

The experimental alloys for studying the structure and properties were melted in the induction furnace IST-006 with a basic lining. The heat treatment of the samples was carried out in an oxidizing environment.

We alloyed Hadfield steel with nitrided ferrochrome, the chemical composition of which is shown in Table 1.

The studies were carried out on standard samples of sizes 35 × 35 × 10 mm. To implement different cooling rates an alloy was poured into different types of moulds: dry and wet sand-clay moulds (SCM), a chill. The change in the metal temperature was registered with the formed tungsten-rhenium thermocouple; the results were recorded with the device LA-50USB with a frequency of 50 Hz per each channel.

The chemical composition of the samples was determined on the SPECTRMAX spectrometer.

We analysed the grain size and the quantity using a Meiji optical microscope with the help of Ticsomet-Standart Pro program in accordance with the GOST 5639-82. Polished sections of the sample were prepared for microanalysis according to the standard method by

Table 1.The chemical composition of nitrided ferrochrome FHN - 10.

Element	Cr	C	Si	P	S	Al	N
Weight (%)	66,2	0,06	0,72	0,003	0,004	0,09	11,1

mounting the samples in resin «Transoptic» on the automatic mounting press Simplimet 1000 on Buehler fully automated sample preparation line. The microstructure was detected by etching the microsection surface in 4% nitric acid solution in ethanol byembedding polished surface into a bath with a reagent.

We carried out the scanning electron microscopy and micro X-ray spectral analyses using a scanning electron microscope JSM-6490 JEOL LV with INCA Energy system at an accelerating voltage of 30 kV. The studies were carried out on microsections used for light microscopy, in secondary electron modes by increasing the magnification from 30 to 50,000 times (the research was carried out in the Centre for Collective Use of the Research Institute of NanoSteels of Nosov Magnitogorsk State Technical University).

We used the standard method for measuring the microhardness with the Buehler hardness tester Micromet in accordance with the GOST 9450-60.The microhardness was calculated from the size of an impression produced under load by a pyramid-shaped diamond indenter with a 136° angle between the opposite faces under a load of 200 g and a loading time of 10seconds. We measured the hardness values using a hardness tester EmcoTest M4C 075 G3 in accordance with the GOST 9013-59.

We studied the abrasive wear resistance of the alloys in accordance with the GOST 23.208-79, the impact-abrasive wear resistance in accordance with the GOST 23,207 - 79.

RESULTS AND DISCUSSION

We received the experimental samples after a series of experiments on smelting and alloying high manganese steel 110G13L with nitrided ferrochrome FHN - 10. Their chemical composition in the cast and heat-treated states is shown in Table 2.

The test results of the samples obtained on the abrasive and impact-abrasive wear resistance, expressed in terms of wear resistance coefficients are presented in Table 3.

According to the data presented in Table 3, the cast steel under the study has the maximum abrasive wear resistance coefficient (> 2.0 units) with the chromium content about 2.0 %. When the content of chromium is more or less this coefficient reduces by 15 - 20 %. Such a tendency is typical for all the experimental samples,

Table 2. The chemical composition of the experimental samples obtained.

N	The concentration of chemical elements													
	C (%)		Si (%)		Mn (%)		P (%)		S (%)		Cr (%)		Al (%)	
	*	**	*	**	*	**	*	**	*	**	*	**	*	**
1	1,15	0,60	1,05	0,65	11,6	11,3	0,04	0,050	0,033	0,045	0,85	0,84	0,08	0,40
2	1,10	0,59	1,18	0,81	11,75	9,8	0,04	0,046	0,035	0,048	1,40	1,35	0,08	0,16
3	1,07	0,70	0,90	0,87	11,55	11,7	0,04	0,050	0,032	0,045	1,91	1,90	0,06	0,71
4	1,20	0,33	0,74	0,93	11,60	10,4	0,04	0,056	0,033	0,032	2,15	2,08	0,06	0,05
5	1,15	0,42	1,08	0,98	11,75	11,3	0,04	0,043	0,033	0,040	3,15	3,15	0,07	0,54

**the element content before heat treatment; **the element content after heat treatment*

Table 3. The values of the abrasive and impact-abrasive wear resistance coefficient depending on the chromium concentration in the steel, the mould type, and the metal state.

Nofsa mple	Abrasive wear resistance			Impact-abrasive wear resistance		
	a wet SCM C/HT	a dry SCM C/HT	a chill C/HT	a wet SCM C/HT	a dry SCM C/HT	a chill C/HT
1	1,0/1,38	1,25/1,39	1,09/1,48	- / -	- / -	- / -
2	1,67/1,28	1,62/1,31	1,76/1,23	1,59 / 1,2	1,43 /1,4	0,91 / 0,99
3	1,55/1,32	1,47/1,41	1,58/1,25	1,76 / 1,14	1,14 /1,13	0,88 / 1,17
4	2,08/1,19	2,05/1,44	2,11/1,35	2,11 / 1,66	0,87 /0,89	1,42 / 1,32
5	1,8/1,23	1,74/1,5	1,83/1,29	1,59 / 1,46	0,83 /0,67	2,33 / 1,15

C - in the cast state; HT - in the heat-treated state

Table 4. The change in the average austenite grain size (R, μm) and its anisotropy factor (A, unit) depending on the content of the alloying element, the type of the mould, the cast state.

Cr content (%)	The cast state						After heat treatment					
	a dry SCM		a wet SCM		a chill		a dry SCM		a wet SCM		a chill	
	R	A	R	A	R	A	R	A	R	A	R	A
0,8	145,9	2,0	106,0	1,9	13,6	1,6	153,3	2,0	108,0	1,8	18,8	1,3
1,4	146,6	2,2	107,5	2,0	18,5	1,8	158,8	2,1	109,9	1,8	27,2	1,5
1,91	159,7	3,6	150,4	3,5	52,3	4,0	173,5	2,3	159,6	2,3	101,8	2,7
2,15	224,0	3,7	174,0	3,8	152,2	4,4	262,8	3,3	257,9	3,4	227,8	3,3
3,15	300,1	4,0	253,2	4,2	222,3	5,1	410,6	3,5	297,6	3,7	286,3	4,5

regardless of the cooling rate of the alloy in the mould, i.e. the type of the mould, which is filled with samples.

Heat treatment reduces the abrasive wear resistance coefficients of the experimental samples by 23 - 36 %. The maximum value of the coefficient (1.5 units) was reached on a sample poured into the dry sand-clay mould with the chromium content of 3.15 %. The values of wear resistance coefficients for the samples poured into the dry SCM increase with increasing the chromium concentration in the steel. The values of wear resistance coefficients for the samples poured into the wet SCM decrease when the chromium concentration is more than 2.0 %.A similar dependence is typical for the samples poured into a chill mould [11].

The wear resistance coefficient in the cast state is determined by the presence of the secondary phase, its morphology, as well as by its location in relation to the austenite grain.

The following factors: the size of austenite grains, its anisotropy (length-to-width ratio) the distribution of chemical elements between austenite and the excessive phase have a substantial impact on the wear resistance coefficients in the cast state. Moreover, in both cases the microhardness of austenite will affect the wear resistance, which varies depending on the degree of alloying of austenite with chemical elements, varying depending on the cooling rate of the melt in the casting mould, as well as the state of the metal (cast, heat-treated).

Table 4 presents the aggregate data on the effect of alloying chromium, the cast state, and the type of the mould on the average austenite grain size, its anisotropy.

According to the data presented in Table 4, the increase in the concentration of chromium in Hadfield steel results in an increase in the average austenite grain size both in the cast and in heat-treated states regardless of the type of the mould. An increase in the cooling rate of the melt in the casting mould (a dry SCM – a wet SCM – a chill) results in a decrease in the average grain size in the cast state and after heat treatment.

An increase in the chromium content in the steel results in an increase in the anisotropy factor of the austenite grain, i.e. increases its «elongation» both in the cast and heat-treated states.

Simultaneous increasing the chromium concentration in the steel and the cooling rate for the alloy in the casting mould results in an increase in the coefficient under consideration.

An increase in the amount of chromium in the steel and the cooling rate during crystallization results in an increase in grain anisotropy (elongation). After heat treatment, the grains become more rounded that results in the reduced anisotropy factor.

The maximum anisotropy factor was observed when the chromium content was about 2.0 %. With the same chromium content, we observed quality change in the character of the effect of cooling rate on its value. When the chromium concentration is less than 2.0 %, an increase in cooling rate of the alloy in the mould facilitates the reduction of the anisotropy factor; the opposite picture is observed when the chromium content is more than 2.0 %. It should be noted that there can be observed a tendency for cast and heat-treated states [11].

Alloying with nitrided ferrochrome results in a change in the austenite microhardness (Fig. 1).

An increase in the chromium concentration results in the increased microhardness of austenite in the cast state by 8 %, in the heat-treated state by 17 %. It should be noted that the average value of the microhardness of austenite both in the cast and in heat-treated states increases with increasing the speed of its cooling in the

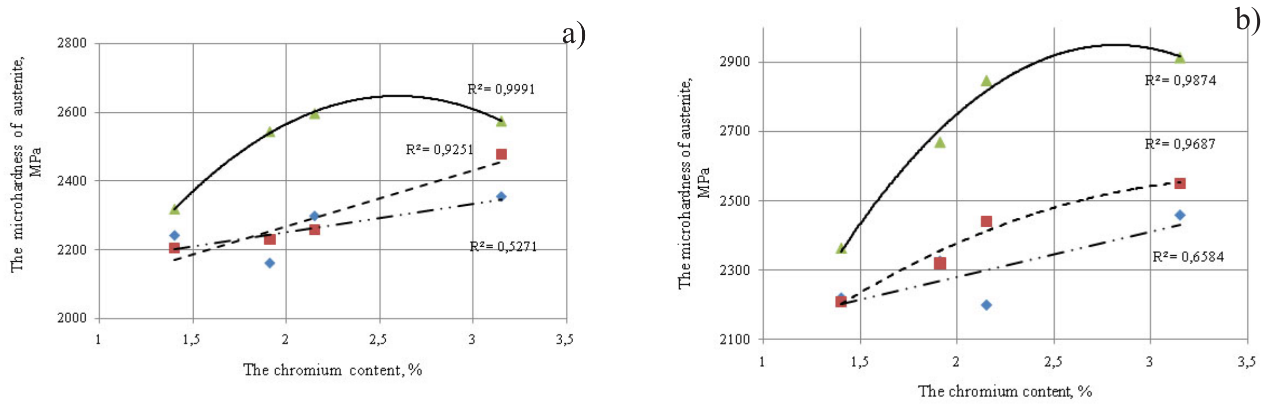

Fig. 1. Dependence of the microhardness of austenite on the chromium content in the steel before the heat treatment (a) and after the heat treatment (b): - a dry SCM; - a wet SCM; - a chill.

casting mould. This is due to the increased degree of alloying austenite with chromium and manganese that, in turn, results in the reduced amount of the carbide phase [19, 20]. At the same time, the hardness value of steel ranges from 84 to 90 HRB.

The effect of cooling rate of the melt in the temperature range of the secondary phase precipitation manifests itself in the austenite grain volume distribution of chemical elements, in particular manganese and chromium.

We carried out a series of experiments to reveal the distribution of the two main alloying elements (Cr, Mn) in the austenite grain volume and the effect of the melt cooling rate in the temperature range of the secondary phase precipitation on this process. An alloy with the constant chemical composition (composition N 1, see Table 2) was poured into the moulds at different heat storage capacity. This resulted in seven samples cooled at rates in the crystallization temperature range from 1.1 to 25 °C/s, and in the range of the secondary phase precipitation from - 14.4 to 327.6 °C/min. Thereafter, we carried out the micro X-ray spectral analysis of the austenite grains of the samples obtained. To obtain correct results on each sample we examined at least 35 austenite grains and then calculated the average value of the manganese and chromium concentration. In order to level the effect of the quality of sample preparation for research, we took the ratio of iron to manganese and chromium in various regions of the austenite grain (centre, border). The results obtained are shown graphically in Fig. 2.

After having analyzed Fig. 2, we found that the manganese and chromium content in the centre and near the austenite grain boundaries is different.

The ratio of iron to manganese and chromium has a higher value with minimal cooling rates (< 50 °C/min) than in the region of higher rates. This indicates a low concentration of these elements in austenite. With such cooling rates, a large amount of the carbide phase is pre-

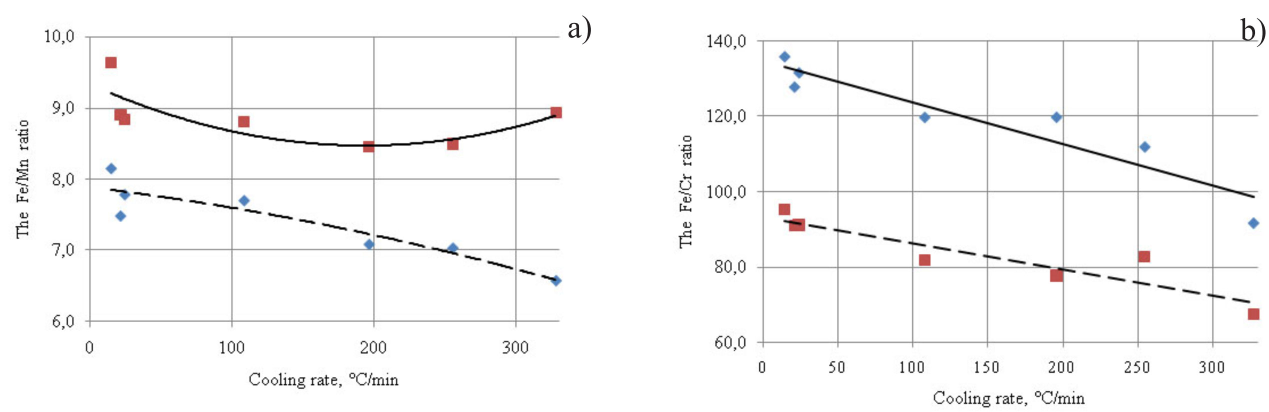

Fig. 2. Change in distribution of iron, manganese, and chromium in the austenite grains depending on cooling rate of the alloy in the mould: - a grain boundary; - the grain centre.

cipitated (14.8 %) [19, 20]. Increased cooling rate in the temperature range of the secondary phase precipitation to a value of 100-150 °C/min results in reduced time while maintaining the melt in the liquid state, the increased speed of the crystallization front, and deceleration of diffusion processes. This results in the increased amount of manganese and chromium in the austenite grains that causes a reduced range in the values of the ratio of iron and these elements. At the same time, decreased amount of the carbide phase to 2.8 % can be observed.

Increased cooling rate of the melt more than 300 °C/min results in a further increasing concentrations of these elements in the austenite grains and reducing carbides at the grain boundaries to 2.1%. Under these cooling conditions, the amount of diffused manganese from the centre to its austenite grain boundary decreases. In this case, some part of manganese, in a small amount located at the grain boundary, is partially precipitated in the carbide phase; this results in its decreased quantity in the grain and increased Fe/Mn ratio.

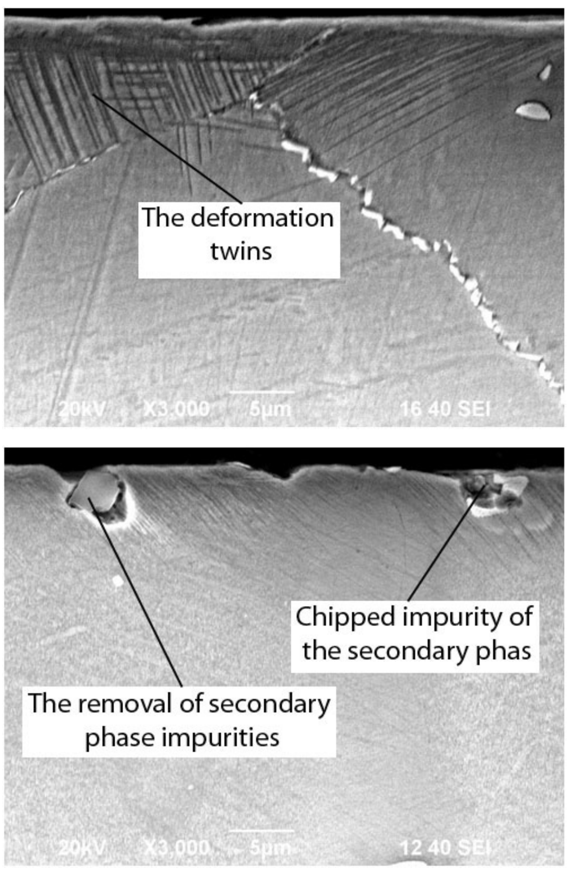

Fig. 3. The worn surface microstructure of the cast high manganese steel: a - the deformation twins; b– impurities of the secondary phase.

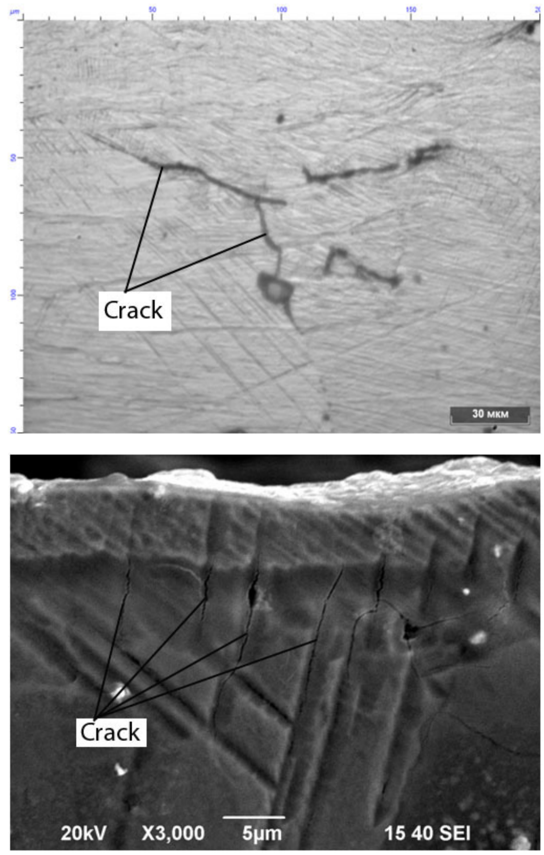

Fig. 4. The austenite cracking in the abrasive wear process.

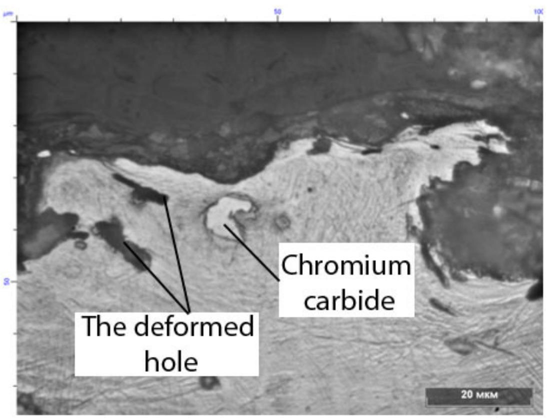

Fig. 5. The surface of the high manganese steel after impact-abrasive wear.

At the same time, the chromium concentrations both in the austenite grain centre and near its borders increase. This results in a monotonic decrease in Fe/Cr ratio curves.

In order to assess the effect of the structure of high manganese steels on the wear resistance we examined the experimental samples both in the cast state and after heat treatment. In addition to the alloy microstructure,

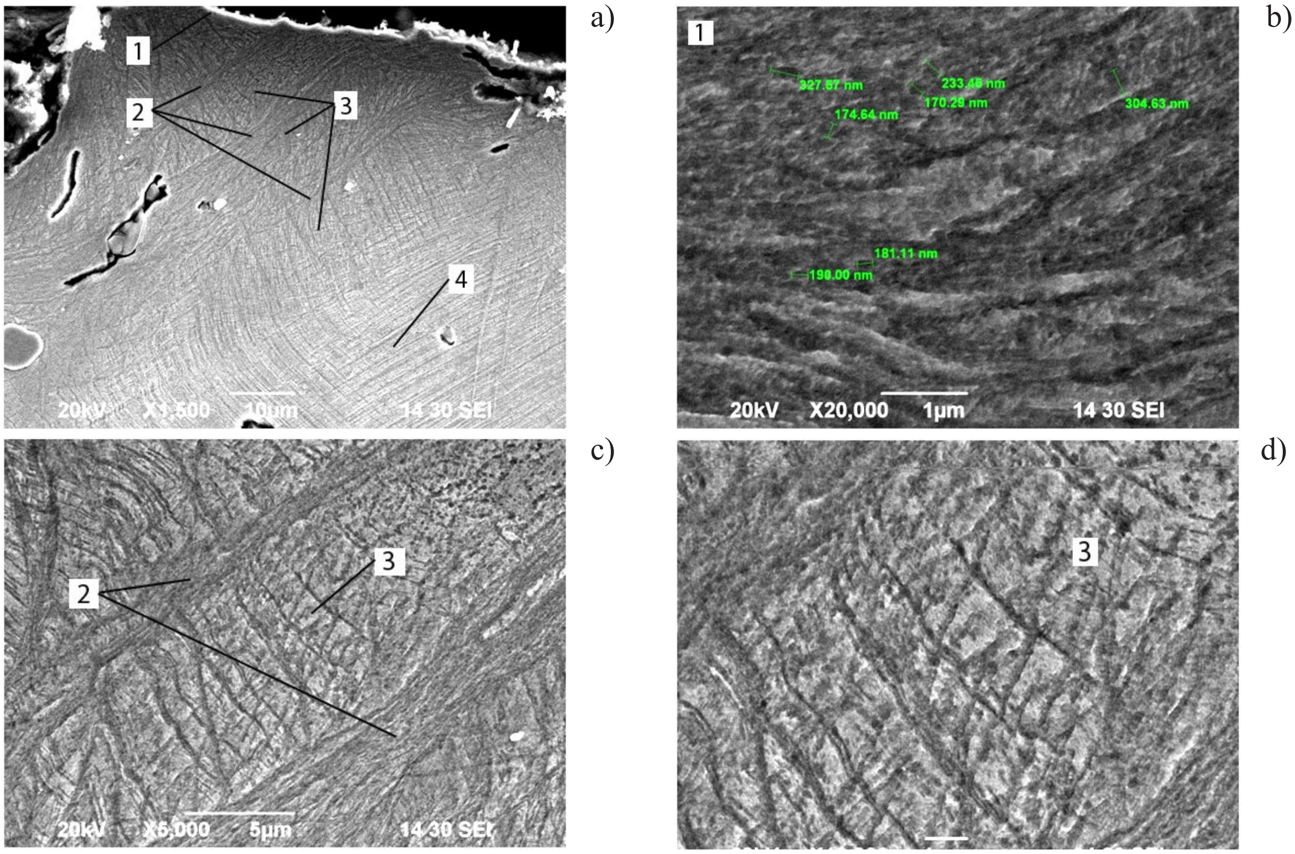

Fig. 6. Location of structural regions in the surface, formed in the process of impact-abrasive wear: a - a general view; b - a region of the ultrafine grain; c - a region of alternating. layers with deformation twinning and martensite; d - a layer of martensite: 1 - the ultrafine grain; 2 - deformation twins with strong consolidation; 3 - the martensite; 4 - deformation twins with normal consolidation.

we studied the surface after different types of wear: abrasive and impact-abrasive.

The contact of the abrasive with the steel surface takes place in any wear process. As a result, transformations by the mechanisms of deformation twinning or dislocation glide occur in the contact surface. The resulting structure is shown in Fig. 3a.

The preferential orientation of the deformation twins (Fig. 3a) is different in the neighbouring grains. Moreover, there can be several orientations within one austenite grain. In Fig. 3, in addition to the twins, the secondary phase impurities are presented with the range in size from 0.5 to 3 μm.

The role of the secondary phase – the manganese and chromium carbides is toprevent austenite from abrasive micro cutting. Likewise, the loading of the device working element on the wear is transmitted to austenite through the carbides and results in deformation conversions therein. It should be noted that an increase in the size and amount of the carbide phase due to low cooling rates of the melt in the mould results in the increased thickness of the hardened layer.

Various kinds of carbides have different wear resistance. During the abrasive wear, chromium carbides are removed from austenite, while manganese carbides are disintegrated (Fig. 3b). The holes remained after these processes facilitate to the intensification of wear processes in these regions.

The reduced rate of the abrasive wear resistance, when the content of chromium in the steel is more than 3 %, is due to the wear surface cracking (Fig. 4). The origin of the cracks often starts near the secondary phase impurities.

After having examined the surface of the experimental samples, we determined that microchipping of manganese impurities can be observed in the process of impact-abrasive wear. The nascent holes, which are deformed in this case, become flattened and elongated.

Chromium carbides retain their integrity throughout the wear process until the time they are removed from austenite (Fig. 5). The deformation twins were also detected in the wear surface.

After extend studies of the surface of the experimental samples, formed after the impact – abrasive wear, a number of its distinctive features have been revealed.

Such a surface includes different types of structures formed under impact loads and arranged in layers. The structures replace each other forming a hardened layer (Fig. 6).

The first layer that contacts with the abrasive is an ultrafine one, i.e. it has the nanostructure parameters (Fig. 6). Under these wear conditions, its thickness does not exceed 3 μm, and the grain size ranges from 170 to 330 nm. Ultrafine grains result from intensive and multiple occurrence of deformation processes in the surface area under study.

Further, there is a heavily compressed layer of deformation twinning. It follows a layer of martensite, having a characteristic needle structure. These two alternating layers form a layered structure comprising from two to five of each layer. It should be noted that the martensitic transformation proceeds with increased steel specific volume that facilitates compression of more ductile adjacent regions of the alloy. This leads to the existence of deformation twins with strong consolidation in a worn surface of layers.

The hardened layer ends with the region of deformation twins with normal consolidation (Fig. 6).

CONCLUSIONS

It was experimentally determined that the steel in which the chromium content is about 2.0 % has the maximum value of the wear resistance coefficient.

The increased concentration of chromium in the chemical composition of steel results in an increase in the total amount of carbides in the structure of cast alloy and a simultaneous decrease in the proportion of manganese carbides and an increase in chromium carbides.

The effect of chromium and cooling rate on the anisotropy of the grain was determined.

When the concentration of chromium in the chemical composition of the high manganese steel is about 2.0 % there is a qualitative change in the effect of cooling rate of the alloy in the mould on the austenite grain anisotropy factor.

The high manganese steel with the chromium content of 2.0% has a maximum microhardness value.

During the abrasive wear of the high manganese steel, deformation transformations resulting in the hardened layer take place. Manganese carbides are destroyed under the abrasive action but chromium carbides are removed from austenite as in the case of testing this steel on impact - abrasive wear.

Moreover, the formation of the hardened layer comprising an ultrafine grain region, a region of deformation twins with strong and normal consolidation, and a martensite region can be observed in the process of impact - abrasive wear.

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