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Influence of Alloying and Heat Treatment on the Abrasive and Impact–Abrasive Wear Resistance of High-Manganese Steel

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Abstract—The basic factors that affect the wear resistance of high-manganese steel are considered. The literature on this topic is reviewed. Conclusions are formulated regarding the materials used in existing studies. Research topics of interest to enterprises that manufacture and employ Hadfield steel are identified. Materials used in the machining of liquid steel are considered. Production technology for experimental high-manganese steel parts is discussed. The composition of the alloy employed as the base is analyzed. The procedure and equipment used to determine the cooling rate of alloys in the mold and to study the wear resistance in conditions of abrasive and impact–abrasive wear are outlined, as well as methods of thermal analysis. Results are presented for the alloying of Hadfield steel by nitrided ferroalloys and other alloys. The coefficients of abrasive and impact–abrasive wear resistance are plotted for different alloying conditions. In addition, the influence of the alloying elements on the wear resistance of high-manganese steel in different wear conditions is studied. The concentrations of the alloying elements corresponding to maximum abrasive and impact–abrasive wear resistance are established. In addition, the results of thermal analysis are presented. The heating of Hadfield steel castings prior to quenching is considered. The temperature ranges corresponding to processes such as excess-phase deposition, the solution of cementite in austenite, and complete solution of phosphide eutectic and metal carbides are established. The temperature limits of oxidation and decarburization of the steel are also determined. On the basis of the results, recommendations are made with a view to increasing the wear resistance of castings made from high-manganese steel for different operating conditions and also to selecting the heat-treatment temperature for such castings.

Keywords: high-manganese steel, nitrided ferroalloys, alloying, austenite, wear resistance, excess phase, quenching

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Factors that affect the wear resistance of cast high-manganese steel components include the alloy composition, the heat-treatment conditions, and the wear conditions. To improve the performance of such components, the steel is alloyed with various materials in the casting shop [1, 2].

The literature includes experimental and production data on the alloying and modification of high-manganese steel by materials such as chromium [3]; the titanium–boron–calcium complex [4]; molybdenum, nickel, and rare-earth metals [5, 6]; calcium and barium and also strontium carbonates [7, 8]; a ferrosilicoaluminum complex with titanium [9]; niobium [10]; aluminum [11, 12]; and copper [13]. In those studies, however, attention focuses on the microstructure and mechanical characteristics, which are not always directly related to the overall performance.

In addition, no literature data are available regarding the combined influence of the thermal conditions in the casting shop (the rate of alloy cooling) and the specific alloying on the properties of high-manganese steel. In casting, the cooling rate of the alloy may change as a function of the metal content in the mold and the casting dimensions. The cooling rate of the alloy in the mold will affect the distribution of alloying elements between the secondary phase and the austenite, with corresponding change in the degree of alloying of the austenite [14, 15]. This, in turn, will determine the properties of Hadfield steel, as well as its wear resistance.

High-manganese steel components undergo heat treatment to ensure solution of the secondary phases at the grain boundaries [16, 17]. On alloying and modification of the steel, new types of carbides and nitrides are deposited. The design of the heat treatment calls for knowledge of the temperature intervals corresponding to solution of the newly formed excess phases. Such data are missing from the literature.

The conditions in which high-manganese steel components are subjected to wear significantly affect the outcome. Asa rule, high-manganese steel components operate in conditions of abrasive wear (bucket

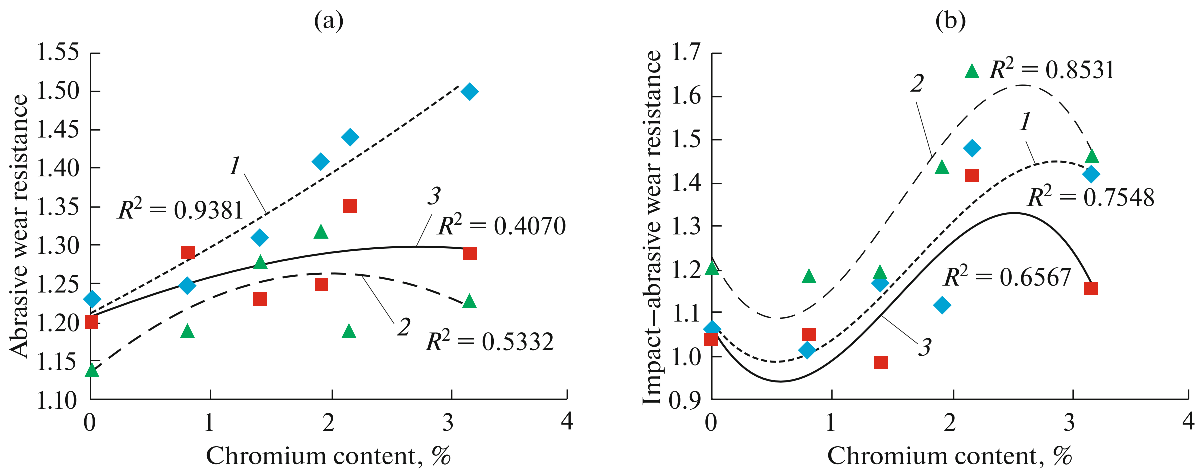

Fig. 1. Influence of the alloying of Hadfield steel with nitrided ferrochrome on the abrasive (a) and impact–abrasive (b) wear resistance when the cooling rate of the alloy in the mold is 4.5°C/s (*1*), 8.9°C/s (*2*), and 25°C/s (*3*).

teeth of excavators, crusher channels) or impact–abrasive wear (crusher jaws and hammers) [18]. With difference in the external conditions, the process in the alloy is fundamentally different. The wear resistance of steel of fixed chemical composition will differ considerably in abrasive and impact–abrasive wear.

Thus, in the present work, we study the influence of the chemical composition of high-manganese steel and the cooling rate of components in the mold on the abrasive and impact–abrasive wear resistance. We also establish the temperature parameters of heat treatment for different alloy compositions.

We investigate cast high-manganese steel samples, with the following basic composition (wt %):

C	Si	Mn	S	P	Cr	Ni	Al
1.2	0.9	12.3	0.024	0.033	0.8	0.12	0.06

The chemical composition of the sample is determined on a SPECTRO MAXx spectrometer.

To permit cooling of high-manganese steel at different rates, the alloy is cast in molds with different thermal characteristics: dry and raw sand–clay molds or a chill mold. The temperature variation of the cast metal over time is recorded by means of tungsten–rhenium thermocouples, which are inserted in the mold in the course of shaping. The results are recorded by means of an LA-50USB analog–digital converter, with a frequency of 50 Hz in each channel. Simultaneous recording in four channels is possible. The cooling rate of the alloy in the temperature ranges corresponding to solidification and cooling is determined from the cooling curve.

The high-manganese steel is alloyed with the following ferroalloys: FKhN-10 nitrided ferrochrome; nitrided titanium–calcium alloy; and nitrided ferrovanadium produced by Etalon (Magnitogorsk). Then the wear resistance of the alloys is determined as a function of the content of alloying elements.

We use a NAKAL resistance furnace for heat treatment of the alloys, in an oxidative atmosphere.

Wear tests are conducted on laboratory apparatus corresponding to State Standard GOST 23.208–79 (abrasive wear resistance) and State Standard GOST 23.207–79 (impact–abrasive wear resistance).

The processes in high-manganese steel on heating before quenching are studied on a Netzsch STA instrument (Jupiter 449 F3) by differential scanning calorimetry and thermogravimetry.

In the experiments, we obtain samples of high-manganese steel alloyed with different quantities of nitrided ferroalloys: ferrochrome; titanium–calcium alloy; and ferrovanadium. Several series of experiments are conducted on the alloying of Hadfield steel with each ferroalloy. On alloying with nitrided ferrochrome, the chromium concentration in the final alloy is 3.15%.

The influence of chromium on the abrasive and impact–abrasive wear resistance is shown in Fig. 1 as a function of the cooling rate of the melt in the mold during solidification. We see that, on alloying high-manganese steel with nitrided ferrochrome, the chromium concentration in the steel must be 2.0–2.5%. With such chromium concentrations, the steel castings will have the greatest resistance to abrasive and impact–abrasive wear.

The increase in wear resistance of the steel after alloying with nitrided ferrochrome is due to the change in macro- and microstructure and also to the formation of chromium carbides. This was considered in detail in [19, 20].

It follows from Fig. 2 that the abrasive and impact–abrasive wear resistance of Hadfield steel is greatest with 0.04–0.08% Ti. Further increase in titanium

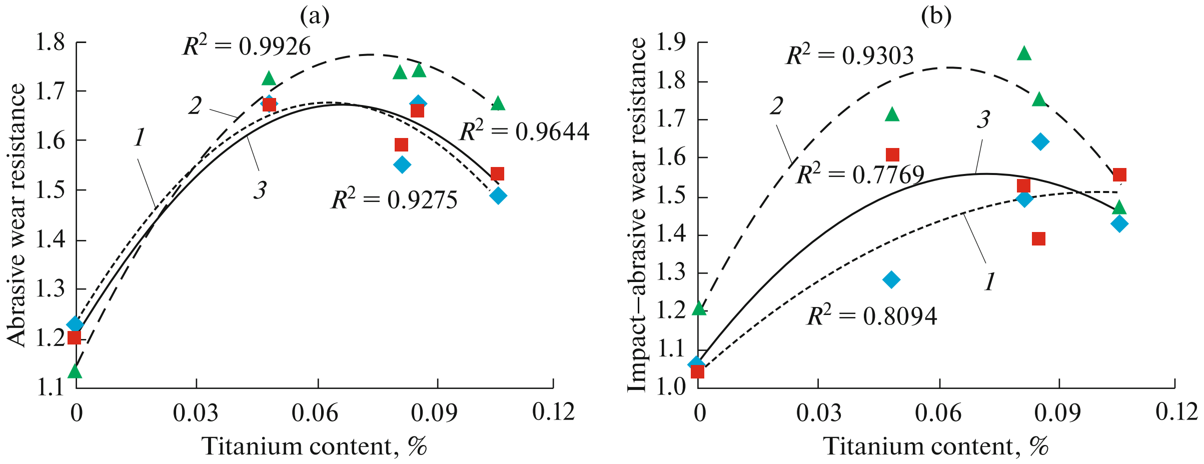

Fig. 2. Influence of the alloying of Hadfield steel with nitrided titanium–calcium alloy on the abrasive (a) and impact–abrasive (b) wear resistance when the cooling rate of the alloy in the mold is 4.5°C/s (*1*), 8.9°C/s (*2*), and 25°C/s (*3*).

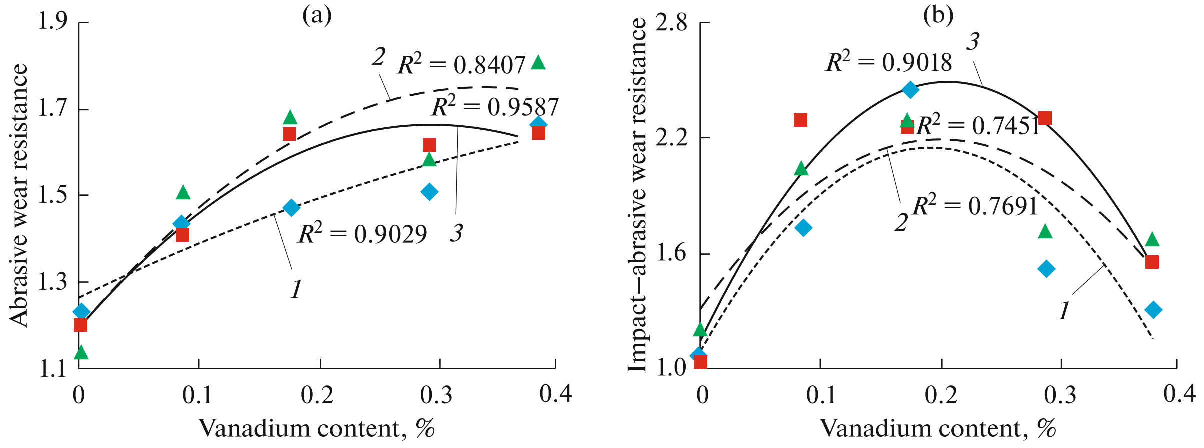

Fig. 3. Influence of the alloying of Hadfield steel with nitrided ferrovanadium on the abrasive (a) and impact–abrasive (b) wear resistance when the cooling rate of the alloy in the mold is 4.5°C/s (*1*), 8.9°C/s (*2*), and 25°C/s (*3*).

concentration decreases the wear resistance. The wear resistance is greatest for steel cooled in the mold at a rate of 8.9°C/s.

The increase in the steel's resistance to impact–abrasive wear is greatest after alloying the high-manganese steel with vanadium. The dependence of the abrasive and impact–abrasive wear resistance of high-manganese steel on the vanadium content in the alloy is shown in Fig. 3.

The vanadium concentration in the alloy is 0.01–0.4%. The abrasive wear resistance of the high-manganese steel components is 30–40% after introducing vanadium, while the impact–abrasive wear resistance is doubled. In abrasive wear, the rate at which the wear resistance increases is greatest up to 0.2%, and then declines. In impact–abrasive wear, increasing the vanadium concentration above 0.2% decreases the wear resistance by 27–35%. The increase in wear resistance is due to the formation of vanadium carbides in place of the phosphide eutectic and magnesium-bearing cementite along the austenite grain boundaries, as in alloying by nitrided ferrochrome [19].

Comparison of Figs. 1–3 shows that alloying with nitrided titanium–calcium alloy is expedient in order to increase the abrasive wear resistance of high-manganese steel. In that case, the residual Ti content in the alloy is 0.04–0.08%. To improve the impact–abrasive wear resistance, the Hadfield steel must be alloyed with ferrovanadium. However, the vanadium concentration must not exceed 0.2%.

In the production of high-manganese steel castings, heat treatment is required to dissolve the eutectic deposited at the grain boundaries on crystallization. Traditionally, the casting is quenched from 1100°C in water, despite the different alloying and modification of the alloys. The casting is heated in a furnace in an

Table 1. Results of differential scanning calorimetry

Alloying additive	Endothermal effect, °C					
	second peak on curve			third peak on curve		
	beginning	peak	end	beginning	peak	end
Nitrided ferrochrome	657	703	752	893	925	945
Nitrided titanium–calcium alloy	633	713	746	923	968	1006
Nitrided ferrovanadium	631	707	743	920	964	1005

oxidative atmosphere. That may lead to some change in alloy composition.

Thermal analysis is employed to assess the kinetics of the phase transformations when high-manganese steel castings are heated prior to quenching.

In differential scanning calorimetry, all the curves have three characteristic peaks. The first is at 283–285°C, regardless of the steel's composition. That corresponds to carbide deposition from the supersaturated solid solution. The second and third peaks correspond to the solution of excess phases (Table 1).

The peak of the second endothermal effect at 631–752°C corresponds to the solution of alloyed cementite. The phosphide eutectic dissolves at higher temperatures (893–1006°C). In the same range, the solution of carbides of the alloying elements ends. Therefore, heating of high-manganese steel castings to 945–1006°C ensures complete solution of the excess phases.

By thermogravimetric analysis, we find that the oxidation of high-manganese steel begins at around 500°C and ends at 900°C. Decarburization begins in the range 900–1000°C. At higher temperatures, the decarburization rate increases, with consequent decrease in carbon content in the alloys by 0.04–0.14%. The decarburization rate is least for alloys with chromium. This may be attributed to the formation of a thick film of chromium oxide at the sample surface, reducing oxygen access to the metal. Alloys with vanadium have the greatest decarburization.

CONCLUSIONS

We find that alloying with nitrided ferroalloys increases the wear resistance of Hadfield steel castings. To increase the abrasive wear resistance, it is expedient to use nitrided titanium–calcium alloy, which ensures a residual titanium content of 0.04–0.08% in the alloy. The abrasive wear resistance is increased by 39–52%, depending on the cooling rate of the melt in the mold. The impact–abrasive wear resistance is doubled on alloying with nitrided ferrovanadium. The vanadium concentration in the alloy must not exceed 0.2%.

Thermal analysis indicates that, on heating the alloy before quenching, excess phases are deposited at 283–285°C. At 631–752°C, we observe the solution of alloyed cementite. Heating of high-manganese steel castings to 945–1006°C ensures complete solution of the excess phases and may be recommended in quenching.

By thermogravimetric analysis, we find that the oxidation of high-manganese steel occurs at 500–900°C. Decarburization begins at 900–1000°C. The decarburization rate increases above 1000°C.

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