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Changes in Impact Strength and Abrasive Wear Resistance of Cast High Manganese Steel Due to the Formation of Primary Titanium Carbides

G. Tęcza *, R. Zapała
Department of Cast Alloys and Composites Engineering, Faculty of Foundry Engineering,
AGH University of Science and Technology, 23 Reymonta Str., 30-059 Kraków, Poland
*Corresponding author. E-mail address: tecza@agh.edu.pl

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Abstract

Cast high-manganese Hadfield steel is commonly used for machine components operating under dynamic load conditions. Their high fracture toughness and abrasive wear resistance is the result of an austenitic structure, which - while being ductile - at the same time tends to surface harden under the effect of cold work. Absence of dynamic loads (e.g. in the case of sand abrasion) causes rapid and premature wear of parts.
In order to improve the abrasive wear resistance of cast high-manganese steel for operation under the conditions free from dynamic loads, primary titanium carbides are produced in this cast steel during melting process to obtain in castings, after melt solidification, the microstructure consisting of an austenitic matrix and primary carbides uniformly distributed therein. After heat treatment, the microhardness of the austenitic matrix of such cast steel is up to 580 μHV_{20} and the resulting carbides may reach even 4000 μHV_{20}.
The impact strength of this cast steel varies from 57 to 129 and it decreases with titanium content.
Compared to common cast Hadfield steel, the abrasive wear resistance determined in Miller test is at least twice as high for the 0.4% Ti alloy and continues growing with titanium content.

Keywords: Cast high-manganese steel, Microstructure, Primary carbides, Microhardness, Impact strength, Abrasion

1. Introduction

Components of crushers, beaters, mill lining, and parts working in the power or construction industry are castings operated under impact conditions. The use of cast high-manganese steel for the aforementioned elements is due to the austenitic structure, which is both ductile and resistant to crack formation as well as capable of strong surface hardening under the effect of impacts. Cast components made from Hadfield steel when operated under the conditions of load-free abrasion suffer a very fast wear. Under such conditions their abrasive wear resistance resembles that of cast unalloyed steel [1 ÷ 6].
The basic chemical composition of cast Hadfield steel in percent by weight can vary in the following ranges of values: 0.9 ÷ 1.4% C, 11.5 ÷ 14% Mn, $\leq$ 1.0% Si, $\leq$0.1% P, $\leq$0.03% S, where the most important problem is observing the Mn/C ratio equal to 10.
At present, the technique often applied is modification of chemical composition with the addition of carbide-forming

elements, such as 1.5 ÷ 2.5% Cr or 1.8 ÷ 2.1% Mo. The aim of this modification is improvement of the abrasive wear resistance of castings. Another alloying additive used frequently in castings of this type is Ni introduced in an amount of 2 ÷ 4%. The addition of nickel is intended to stabilize the austenitic structure in thick-walled castings after their heat treatment [1 ÷ 10]. Hadfield steel castings operating in the industry are often very massive and heavy-walled components. Their as-cast microstructure consists of an austenitic matrix with precipitates of alloyed cementite and non-metallic inclusions. Carbides precipitated during casting solidification and cooling form a continuous network along the austenite grain boundaries, which - combined with their acicular and lamellar shape - greatly reduces the crack resistance (Fig. 1).
The addition of carbide-forming elements such as chromium to the basic composition of Hadfield steel results in the precipitation of even larger amounts of the alloyed cementite not only at the grain boundaries but also inside them, further intensifying in this way the casting tendency to crack formation (Fig. 2). Massive castings are prone to the grain growth, and this effect, combined with the precipitation of a large amount of carbides, greatly increases the cast steel brittleness, making castings unfit for operation under variable impact loads. To make this operation possible, castings should be subjected to a solution heat treatment, which upon cooling of the casting will make its structure composed of the sole austenitic matrix without any precipitates of the alloyed cementite (Fig. 3), [1 ÷ 10]. After solution heat treatment, the microhardness of austenite in castings made from the alloy of basic chemical composition is 340 ÷ 370 μHV_{20} [1,10] while impact strength is comprised in the range of 200 ÷ 250 J/cm^2. These values depend on the grain size in castings and also on the pouring temperature, wall thickness and phosphorus content [2,3,6]. The presence of cementite precipitating along the grain boundaries, coarse grains and elevated phosphorus content drastically reduce the cast Hadfield steel fracture toughness. As claimed by some researchers, the impact strength may suffer a drop to even 25 J/cm^2 [1 ÷ 10].

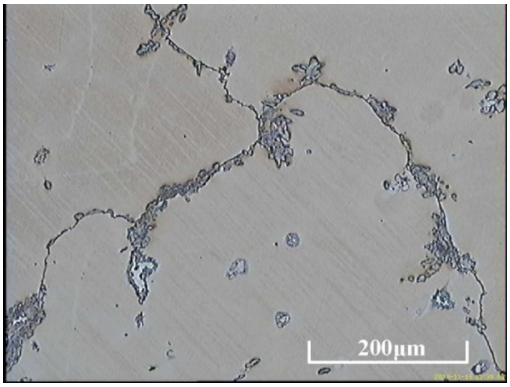

Fig. 1. As-cast microstructure of Hadfield steel; austenitic matrix with precipitates of alloyed cementite; nital etching [1]

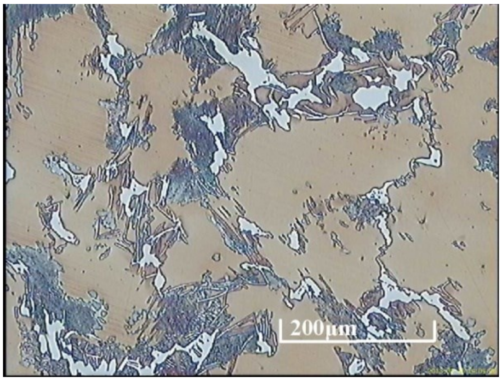

Fig. 2. As-cast microstructure of Hadfield steel with 1.4% Cr; austenitic matrix with numerous precipitates of alloyed cementite; nital etching [1]

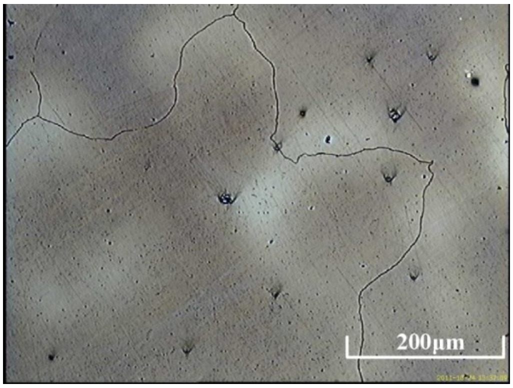

Fig. 3. Microstructure of cast Hadfield steel after solution heat treatment; austenitic matrix free from precipitates of alloyed cementite; nital etching [1]

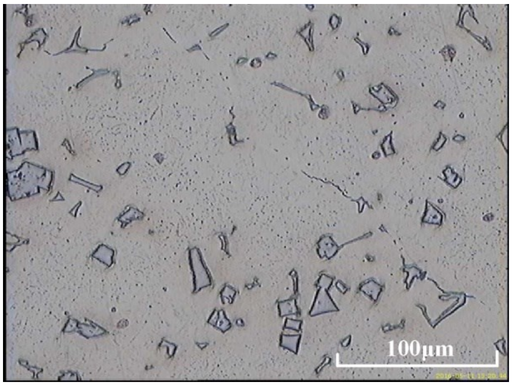

Fig. 4. Microstructure of cast steel (0.8% C, 16% Mn, 1.4% Cr, 2% Ti) after solution heat treatment; austenitic matrix with primary titanium carbides uniformly distributed in this matrix; nital etching [1]

Cases are known in the literature when the addition of about 6% V has been introduced to the cast high manganese steel. With the content of 2.3% C and 11% Mn, the structure consisting of austenitic matrix and eutectic vanadium carbides was obtained. Test castings made from this iron grade had very low impact strength (3 ÷ 6 J/cm^2) [9]. In another case, the authors of [10], at a content of 1.6% C, 10% Mn and 5.5% V, obtained the microstructure consisting of an austenitic matrix and primary vanadium carbides distributed evenly therein. This cast steel in the abrasive test carried out in a water-silicon carbide slurry showed two times higher wear resistance compared to the common cast Hadfield steel. The as-cast matrix microhardness of this steel was about 370 μHV_{20} and it increased to 402 ÷ 438 μHV_{20} after solution heat treatment [10]. A similar type of microstructure was obtained in [1], where at a content of 0.4 to 2.5% Ti in as-cast condition, the microstructure was composed of a high-manganese austenitic matrix and primary titanium carbides evenly distributed in this matrix with a small amount of alloyed cementite precipitated along the grain boundaries. The solution heat treatment of these alloys allowed obtaining the structure composed of an austenitic matrix and primary titanium carbides uniformly distributed therein but without any cementite on the grain boundaries (Fig. 4). The as-cast microhardness of the matrix of this cast steel was observed to increase with titanium content and was between 380 and 510 μHV_{20} . After solution heat treatment, the microhardness of the matrix increased to 580 μHV_{20} , while the resulting carbides could sometimes reach the value of even 4000 μHV_{20} [1].

2. Test materials and methods

Test specimens were cut out from the four Y-type ingots with different carbon and titanium content and a weight of about 8 kg. The ingots were cast from the steel obtained by melting in a 30 kg induction furnace the cast Hadfield iron scrap containing Fe-Ti. To make up the chemical composition, to the molten steel, suitable amounts of carburizer and electrolytic manganese were added in the metallurgical process. The addition of titanium produced primary titanium carbides, which after solidification were evenly distributed in the alloy matrix. The test castings contained 1.2 ÷ 1.4% Cr, 1.5 ÷ 2.4% Si, and Ti in a variable amount of 0.4 ÷ 2.5%. The chemical composition of the test ingots is shown in Table 1.

The test specimens were cut out from a 25 mm wall thickness casting which was next subjected to solution heat treatment at 1050°C with cooling in water. The specimens were used for the impact tests and abrasive wear resistance tests. From the literature review a low impact strength was expected, and therefore 10x10x55 mm unnotched specimens were prepared for the impact tests. Impact tests were carried out on a Pendulum 150 J Charpy impact tester. Wear resistance tests were performed in the Miller machine, which is used to compare the abrasion resistance of different structural materials or of the same material subjected to different heat treatments . The test consisted in placing standard samples in the holders of the machine, loading them with constant force and subjecting to the abrasive effect of a silicon carbide-water mixture (prepared in a ratio of 1: 1). Sixteen-hour lasting abrasion tests were performed in 4 cycles. Every four hours, the tested samples were weighed, and based on the weight loss, the wear curves were plotted. The values of the wear rate calculated for the tested steel after solution heat treatment compared with the wear rate of a sample made from the cast Hadfield steel with standard chemical composition (1.2% C, 13% Mn, 0.8% Si), subjected to standard heat treatment, i.e. the solution heat treatment.

Table 1.
Chemical composition of investigated cast high manganese steel

Chemical composition [wt. %]							
C	Mn	Si	P	S	Cr	Ni	Ti
1.4	14	1.5	0.07	0.003	1.2	0.2	0.4
1.2	13	2.4	0.03	0.02	0.2	0.1	1.5
0.8	16	2.3	0.04	0.03	1.4	0.2	2.0
1.2	15	1.5	0.04	0.02	1.4	0.1	2.5

3. Test results

Analysis of the chemical composition given in Table 1 has revealed the content of basic elements in the cast steel melt comparable to the content in cast Hadfield steel. Table 2 also shows the results of impact tests.

Table 2.
Impact strength of the tested cast high-manganese steel

Titanium content [wt.%]	Average impact strength [J/cm^2]
0.4	129
1.5	83
2.0	71
2.5	57

The results show that, compared to the common cast Hadfield steel, the impact strength of the tested cast steel has been reduced nearly twice and tended to decrease with the increasing titanium content from 129 J/cm^2 for 0.5% Ti to 57 J/cm^2 for 2.5% Ti.

Figure 5 shows the relationship between total sample weight loss and time of abrasion. Detailed analysis of the results proves that the abrasive wear resistance of the tested cast high-manganese steel has increased more than two times compared to the common cast Hadfield steel. The increase in Ti content had little effect on the value of abrasive wear and caused its further decrease.

Figure 6 shows the topography of sample surface after abrasion test. In the cast Hadfield steel, deep scratches and furrows are visible on the surface. The addition of titanium makes the sample wear distribution more uniform. The surface of the sample is even and slightly rough.

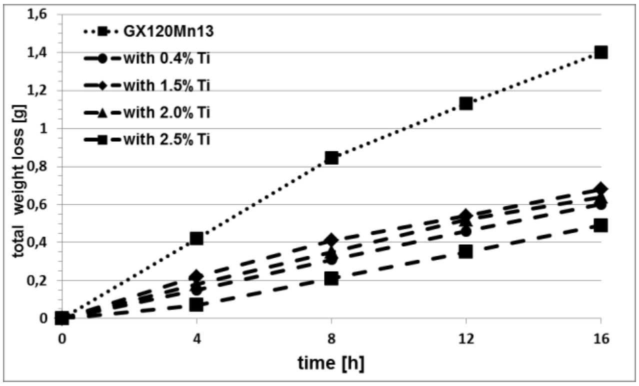

Fig. 5. Total weight losses of investigated cast materials steel after solution heat treated as a function of abrasion time

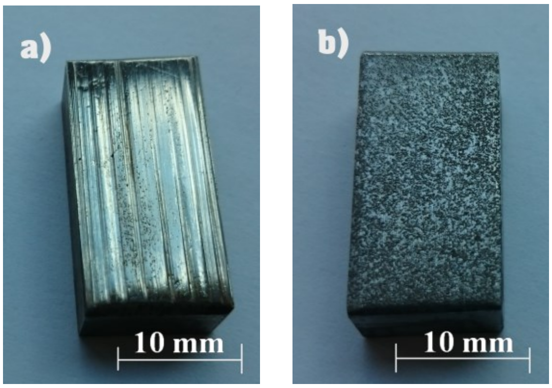

Fig. 6. Sample surface after abrasion test: cast Hadfield steel - a); tested cast steel with 2.0% Ti content - b)

4. Conclusions

The impact strength of the tested cast steel is reduced at least two times compared to cast Hadfield steel.

- The impact strength decreases once the titanium content starts increasing.
- The abrasive wear resistance is more than doubled compared to cast Hadfield steel.
- The increase in Ti content has little effect on total wear of samples.
- The addition of titanium makes the sample wear profile more uniform.

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