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Resistance to Abrasive Wear and Volume Fraction of Carbides in Cast High-manganese Austenitic Steel with Composite Structure

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Abstract

Cast Hadfield steel is characterised by high abrasion resistance, provided, however, that it is exposed to the effect of dynamic loads. During abrasion without loading, e.g. under the impact of loose sand jet, its wear resistance drops very drastically. To increase the abrasion resistance of this alloy under the conditions where no pressure is acting, primary vanadium carbides are formed in the metallurgical process, to obtain a composite structure after the melt solidification. The primary, very hard, carbides uniformly distributed in the austenitic matrix are reported to double the wear resistance of samples subjected to the effect of a silicon carbide-water mixture.

Keywords: Resistance to abrasive wear, Cast high-manganese steel, Solution treatment, Microstructure, Vanadium carbides.

1. Introduction

Cast high-manganese steel containing 1.2% C and 12% Mn, commonly known as Hadfield steel, has an austenitic structure in the as-cast state with precipitates of alloyed cementite and triple phosphorus-carbide eutectic (Fe (Fe, Mn)$_3$C-(Fe, Mn)$_3$P) [1], which occurs when the phosphorus content is above the level of 0.04% [2]. Then the structure also contains the non-metallic inclusions of oxides, sulphides and nitrides (Fig.1). The acicular precipitates of (Fe,Mn)$_x$C$_y$ type carbides spread along grain boundaries [3] reduce the ductility of this cast steel (as reported by Z. Stradomski [4], sometimes even as much as ten times). For this reason, castings are subjected to a heat treatment, which consists in solutionising combined with cooling in water and has as an aim obtaining purely austenitic structure, i.e. the structure free from any carbide precipitates (Fig. 2). Yet, it should be remembered that heavy castings may still contain carbides, undissolved or precipitated during heat treatment, located on the grain boundaries (Fig. 3) and visible only at very high magnification [11,12]. Owing to the excellent wear resistance under the impact of dynamic loads with good ductility preserved, castings made from this steel are used in industry for parts of crushers and mills, for lining plates, hammers, jaws, and cones [2, 5-7,10]. At low loads, or during the abrasive impact of e.g. sand, the abrasion resistance of this cast steel is comparable to cast carbon steel. Castings made from Hadfield steel are usually massive elements with the wall thickness of even up to 100 mm. During their solidification, the segregation of alloying elements such as phosphorus, carbon and chromium takes place [2,3,6-10,16].

The segregation of elements and the precipitation of acicular carbides are more advanced in those alloys which, to improve the abrasion resistance, are enriched with the addition of carbide-forming elements such as chromium or molybdenum (Table 1) (Fig. 4) [2,3,6-10,16].

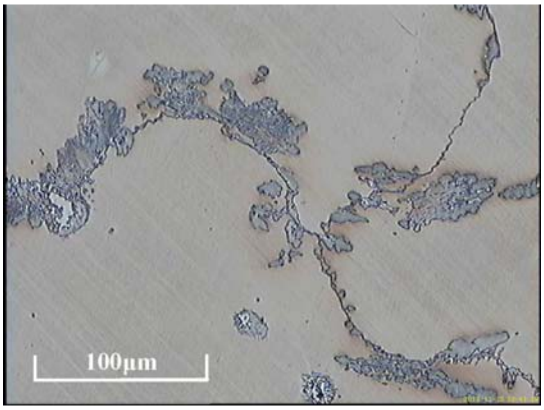

Fig. 1. As-cast Hadfield steel; austenitic matrix with the precipitates of acicular alloyed cementite; nital etched

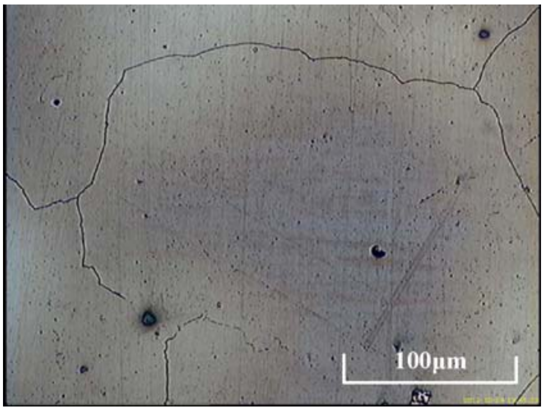

Fig. 2. Cast Hadfield steel after solution heat treatment in water; austenitic matrix free from the precipitates of alloyed cementite on grain boundaries; nital etched

Changing the chemical composition enhances the effect of the segregation of elements and results in the precipitation of an increased number of complex carbides (mainly on and near the grain boundaries), which leads to a differentiated structure on the casting cross-section and causes stresses during solidification and cooling.

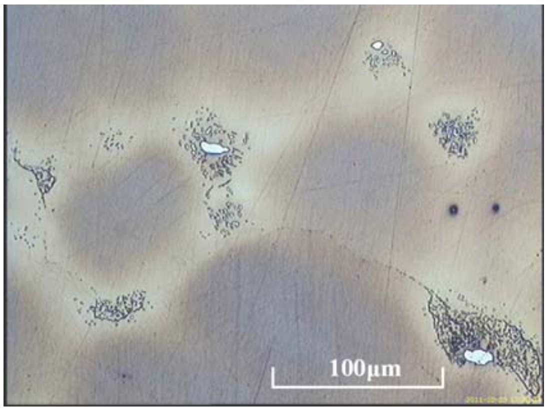

Fig. 3. Cast Hadfield steel after solution heat treatment in water; austenitic matrix with carbides undissolved or precipitated on grain boundaries during heat treatment; nital etched

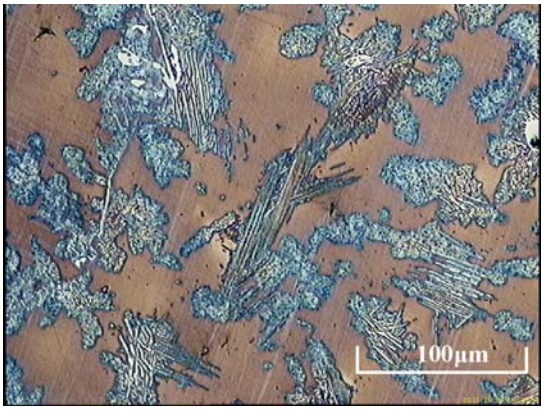

Fig. 4. As-cast Hadfield steel with the addition of chromium (1.5% Cr); austenitic matrix with numerous precipitates of acicular alloyed cementite; nital etched, [16]

Such phenomena may lead to brittle failure of casting either during its operation or even earlier during the manufacturing process. Therefore, in this paper, the authors modified the composition of the Hadfield steel in such a way as to obtain after casting and solidification the structure of a composite consisting of high-manganese austenitic matrix and fine primary carbides, uniformly distributed in the whole volume of this matrix [17].

Table 1.
Examples of the chemical composition of cast austenitic manganese steel [2,5 ÷ 10,14] and of the chemical composition of cast steel examined by the authors

Designation	Chemical composition, [wt%]								
	C	Mn	Si	P	S	Cr	Ni	Mo	V
GX120Mn13	1.12÷1.28	11.5÷14	≤1.0	≤0.07	≤0.03	-	-	-	-
GX120Mn13Cr2	1.05÷1.35	11.5÷14	≤1.0	≤0.07	≤0.03	1.5÷2.5	-	-	-
GX120Mn13Mo2	1.05÷1.45	11.5÷14	≤1.0	≤0.07	≤0.03	-	-	1.8÷2.1	-
Chemical composition of cast steel examined by the authors									
GX160Mn10V6	1.65	9.80	1.94	0.038	-	1.66	0.33	0.05	5.5

2. Test material and methodology

The test material was pilot casting made from high-manganese steel obtained by melting the cast GX120Mn13Cr steel scrap with the addition of Fe-V in an industrial induction furnace. Primary vanadium carbides were produced in the metallurgical process during melting of cast high-manganese steel. The mould pouring temperature was Tzal. = 1550°C. Samples were taken from castings with a wall thickness of 35 mm and were used for chemical analysis, calculation of the volume fraction of carbides, standard solution heat treatment usually applied to cast Hadfield steel, microstructural examinations, measurement of microhardness of phases occurring in the cast steel, and testing of abrasive wear resistance. The volume fraction of vanadium carbides was measured by point method [13], which is based on the equation VV = PP and consists in calculating the fraction of points PP in planar microstructure incident on the examined phase. The required number of grid appositions was calculated assuming the average volume fraction of carbides calculated from the 10 preliminary measurements, the relative error of analysis $\gamma = 0.1$ and the probability that the error of analysis does not exceed the assumed value $1-\alpha = 0.9$ ($\alpha = 0.1$). Altogether 15 grid appositions were made for as-cast samples and 25 for samples after the solution heat treatment. The measurements were taken applying onto the images of unetched microstructure (at a magnification of 2000x) a grid with 120 points of intersection. The measured fraction of points was equal to the relative volume of carbides. Figure 5b shows an example of the as-cast microstructure with the measuring grid deposited on the image. 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 [10,15]. The values of the wear rate calculated for the tested steel in both as-cast state and after solution heat treatment were compared with the wear rate of a sample made from the cast Hadfield steel with standard chemical composition, subjected to standard heat treatment, i.e. the solution heat treatment.

3. Test results

Based on the chemical analysis given in Table 1 it was stated that, compared to standard chemical composition of cast Hadfield steel, the tested cast steel was characterised by an increased content of carbon (1.65%), silicon (1.94%) and chromium (1.66%) and reduced content of manganese (9.80%). The results of examinations carried out by light microscopy have proved that the microstructure of the tested steel in as-cast state and after solution heat treatment consisted of an austenitic matrix and carbides uniformly distributed therein (Fig. 5). The calculated volume fraction of carbides in the as-cast state was 14.6 ± 1.3% and their faceted character indicated that they were primary carbides formed in the liquid phase before metal solidification. Etching of structure also revealed the grain boundaries (Fig. 5a).

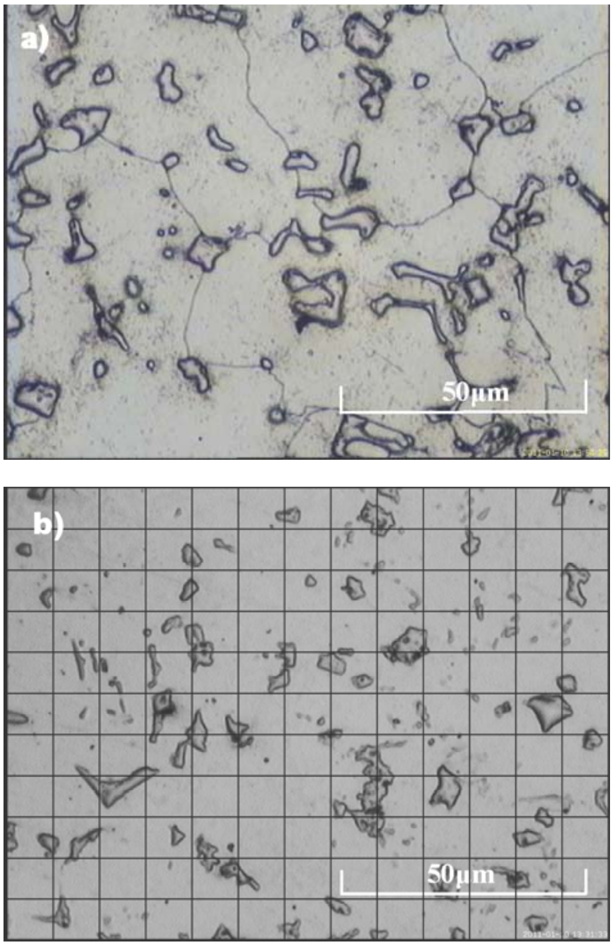

Fig. 5. Cast steel microstructure after solution heat treatment, etched with nital - a); b) - as-cast microstructure with the measuring grid deposited, unetched metallographic section;

The as-cast microhardness of the matrix of the tested steel was comparable to the microhardness of the matrix of standard Hadfield steel, both as-cast and solution heat treated, and amounted to approximately 370µHV. The measured hardness of the produced carbides varied from about 1750µHV to 2650µHV [14] (Fig. 6). The presence of very hard vanadium carbides evenly distributed in the matrix has resulted in a two times higher wear resistance of the tested samples– as a result of 16 hour abrasion cycle, the wear has decreased from 1.4g for standard cast Hadfield steel to 0.7g for the cast steel with composite structure (Fig. 8). After solution heat treatment, the hardness of the tested cast steel matrix has increased to 402 ÷ 438µHV, while its microstructure was still composed of an austenitic matrix and primary carbides uniformly distributed therein (Fig. 7). The fact that vanadium carbides were not dissolved during the solution heat treatment indicates their high stability. Heat treatment and increase in the hardness of the tested alloy matrix reduced further the wear by approximately 25% (Fig. 8). Differences were also observed in surface topography of the tested samples exposed to wear. In the case of standard composition and heat treatment, the surface was worn evenly – it was all smooth with small and shallow scratches;

the surface of the sample containing carbides was worn unevenly – it was rough, dull and with carbides well visible (Fig. 9).

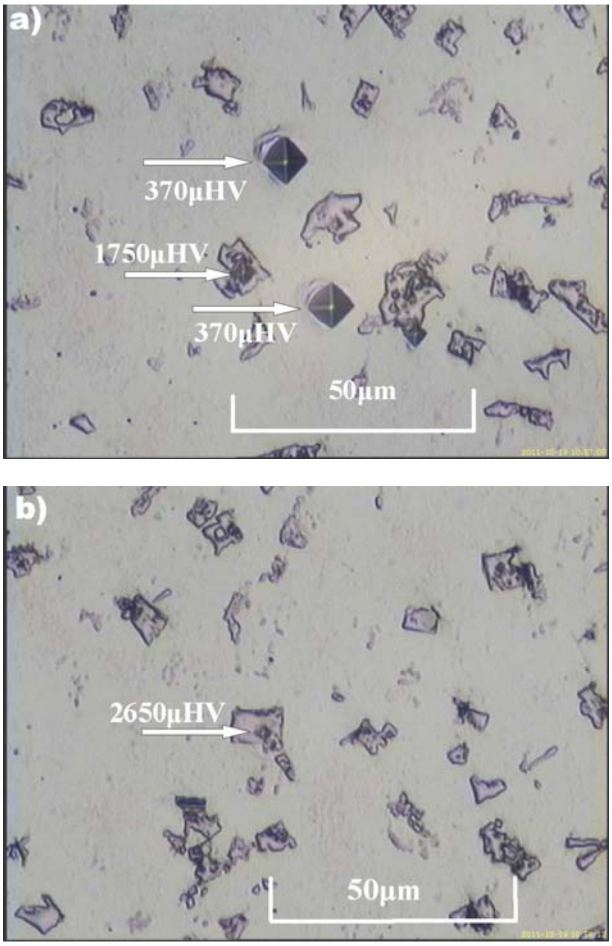

Fig. 6. Microstructure of as-cast steel with marked values of the microhardness of matrix - (a) and carbides - (a and b); unetched; [14]

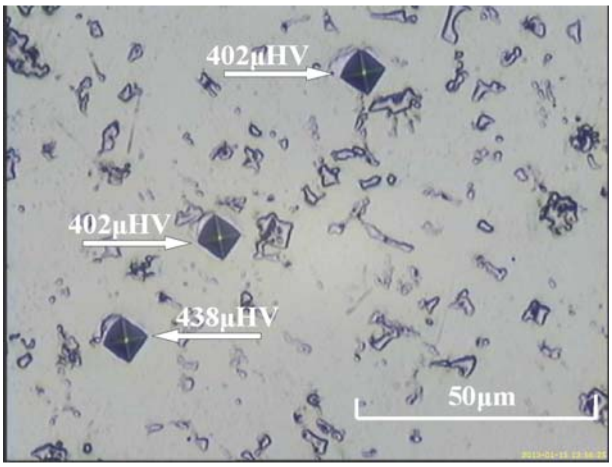

Fig. 7. Cast steel microstructure after solution heat treatment; nital etched;

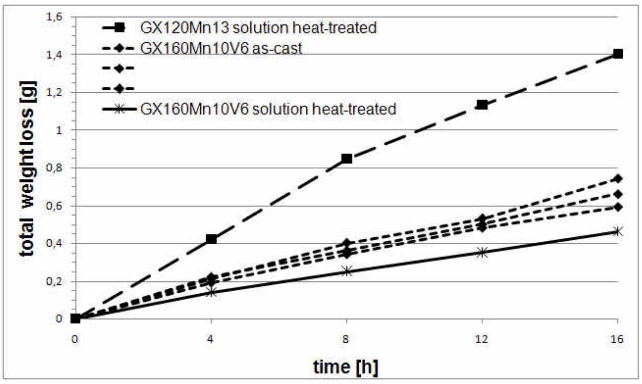

Fig. 8. The wear curves plotted for samples after full abrasion cycle, [14]

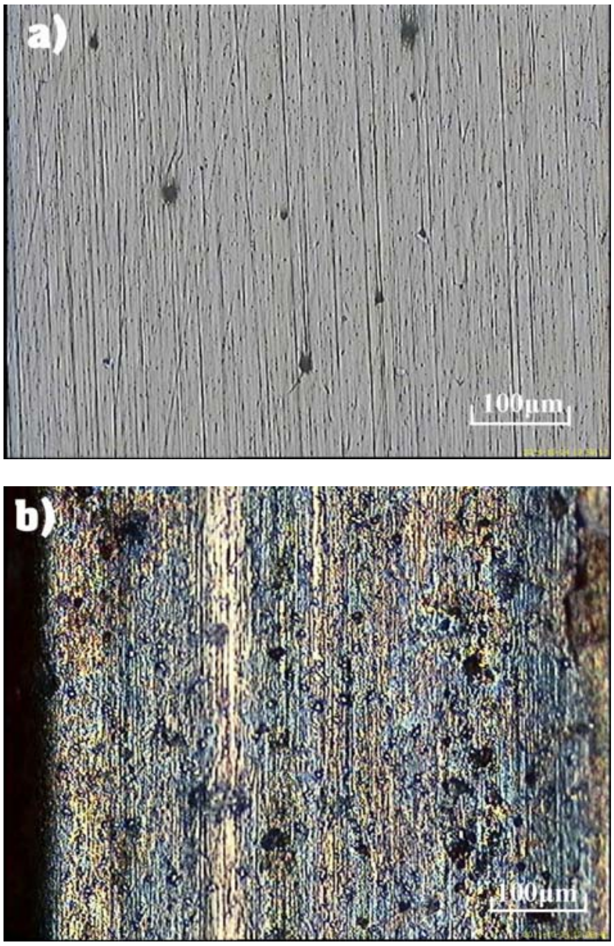

Fig. 9. Surfaces of samples after abrasion test,
(a) – cast Hadfield steel after solution heat treatment,
(b) - cast steel with carbides

4. Conclusions

1. The microstructure of the tested cast steel consists of an austenitic matrix with carbides evenly distributed in this matrix. The faceted nature of vanadium carbides indicates that these are primary carbides formed in the liquid phase.
2. The volume fraction of carbides produced in as-cast state amounts to about 15%,
3. The microhardness of the tested cast steel matrix is comparable to the microhardness of the matrix of standard cast Hadfield steel.
4. After solution heat treatment, the microhardness of the matrix rises to 402 ÷ 438μHV.
5. The hardness of the produced carbides can reach even 2650 μHV.
6. The presence of hard vanadium carbides in the matrix doubles the value of the abrasive wear resistance of the tested cast steel.
7. Heat treatment of the tested alloy results in further reduction of abrasive wear by approximately 25%.

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