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TOOLS CAST FROM THE STEEL OF COMPOSITE STRUCTURE

ODLEWANE NARZĘDZIA ZE STALIWA O STRUKTURZE KOMPOZYTU

Hardness, microstructure and abrasive wear resistance of cast high-manganese steel (cast Hadfield steel) were compared with the cast steel of the same austenitic matrix but having vanadium carbides uniformly distributed within its entire volume. The chemical composition of the cast steel was chosen in such a way as to produce a composite structure after the alloy solidification. A similar hardness of the matrix was obtained with carbides evenly distributed in it, while abrasive wear resistance doubled its value. Using the investment casting process, working elements of teeth for the excavators and mechanical coal miners were cast.

Keywords: Cast tools, primary carbides, composite structure, abrasion resistance

Porównano twardości, mikrostrukturę oraz odporność na ścieranie wysokomanganowego staliwa (Hadfielda) ze staliwem o identycznej osnowie austenitycznej, wewnątrz której rozmieszczone są węgliki wanadu. Skład chemiczny tego staliwa dobrano tak, aby po zakrzepnięciu stopu uzyskać strukturę kompozytu. Uzyskano podobną twardość osnowy, równomierne rozmieszczenie węglików i dwukrotny wzrost odporności na ścieranie. Wykorzystując metodę wytapianych modeli, odlano robocze elementy zębów do koparek lub kombajnów górniczych.

1. Introduction

Making tools by casting method is not a universal process, but it is certainly interesting to the mining and processing industries, to the railway transport and high-tech sectors of industry [1÷3]. There are two variants of this method [1÷4]:

- casting tools from an alloy of the required target chemical composition, or
- casting tools from an alloy of the composition different than the target one, completing the process with subsequent thermal and chemical treatment, e.g. laser treatment [5], applied to the tool working surfaces.

In the latter case, the tool core remains plastic, while the outer working layer offers the required wear resistance [5]. Considering the conditions of thermo-chemical treatment (temperature and time regime) and/or investments for the necessary equipment, the cost of the latter method is relatively high. In contrast to the latter technique, making tools by direct casting is both faster and cheaper, although it requires precision and application of expensive technology (investment patterns). The advantages of the tool casting process are:

- high yield of molten steel (60 to 70% compared to 20 to 40% when rolling or forging process is applied),
- possibility to obtain high ductility of matrix alloy and high abrasive resistance,
- lower cost of production.

Initially, the selection of cast steel grades for tools was based on the previously developed tool steel specification. Tool steels are usually high-speed steels containing large amounts of tungsten and vanadium (and also of molybdenum) [6÷8]. What is essencially demanded from the high-speed steel is the presence of hard and complex carbides of tungsten and vanadium/molybdenum distributed in a uniform manner in a high-strength matrix. The type of carbides and their morphology have a decisive influence on the tool wear and tear rate under the operating conditions. Studies carried out so far were mainly targeted at optimising the chemical composition of steel to reduce its manufacturing costs. Typical examples are inserts and dies for the pressure die casting process made of the Ni12-Co8-Mo8-Ti steel [7]. This steel requires simple heat treatment (to produce martensite) and is resistant to changes in temperature (115 000 shots) [6]. Currently, new techniques and technologies of the tool manufacture are searched for. This means the use of processes such as vacuum melting [10], electroslag remelting [11], powder metallurgy [6] and surface modification of the structure with laser beam [5], thermo-chemical treatment, or application of wear resistant layers [8,9]. The beneficial use of laser allows obtaining high hardness and strength of the steel without reducing its toughness, all this preferably matched with structure refinement and homogenisation. The newly developed technologies

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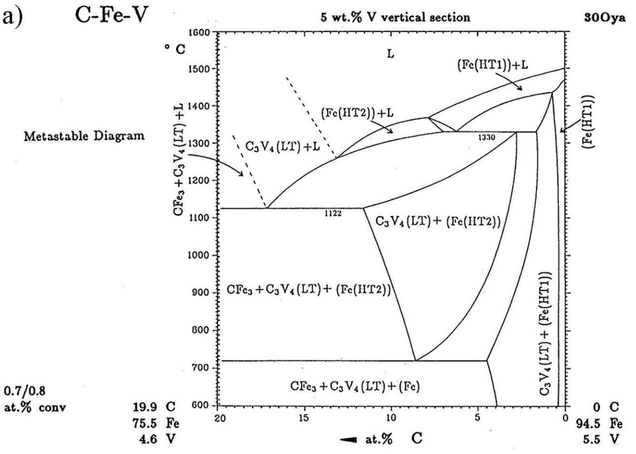
not only lead to structure homogenisation, but also result in two - or three-fold increase of toughness combined with the reduced content of harmful impurities (sulphur and phosphorus down to 0.005%). Melting of tool steel in vacuum and its secondary metallurgy (AOD) [6] mean further improvement in the purity of this material (less of non-metallic inclusions, reduced segregation of elements and carbide/sulphide formation, elimination of microporosity). The improvement in manufacturing techniques is usually combined with the use of such a heat treatment that will eliminate the segregation of carbon, chromium and molybdenum, ultimately leading to an "ultra-fine grain structure" [6,13].

There are also other techniques for the manufacture of cast tools. Some attention certainly deserves hot isostatic pressing (HIP) [10,16,17], the essence of which consists in reproducing the tool shape still within the range of liquidus-solidus temperatures. In this way, all microporosities and shrinkage porosities can be eliminated nearly completely.

2. Background and technological concept

Both tool steels and cast steels should have good abrasive resistance, high hardness and satisfactory ductility at elevated temperatures. These properties depend on the morphology of MC and M_2C type carbides present in the alloy matrix. Due to the presence of "coarse" MC carbides in as-cast condition, the ductility of cast steel suffers considerable drop [4,6]. The processes of precipitation, especially of primary carbides, depend on the solidification rate. This applies mainly to the cast tool steel, whose solidfication range may go up to even 250°C [1,10]. This causes strong segregation of elements (carbon, chromium, tungsten, vanadium) which, together with the solidification rate, determine the resulting microstructure. According to the phase equilibrium diagram of an C-Fe-Mn and C-Fe-V system (Fig. 1a, 1b), the solidification proceeds according to the following sequence: primary crystallisation of δ ferrite, its peritectic $\delta \rightarrow \gamma$ transformation, the formation of $\gamma+$ MC and M_2C eutectic carbides in the interdendritic spaces of the liquid steel. As a final result, the microstructure of the (cast) steel consists of primary carbides distributed in the interdendritic spaces of high-alloyed austenite (Fig. 2).



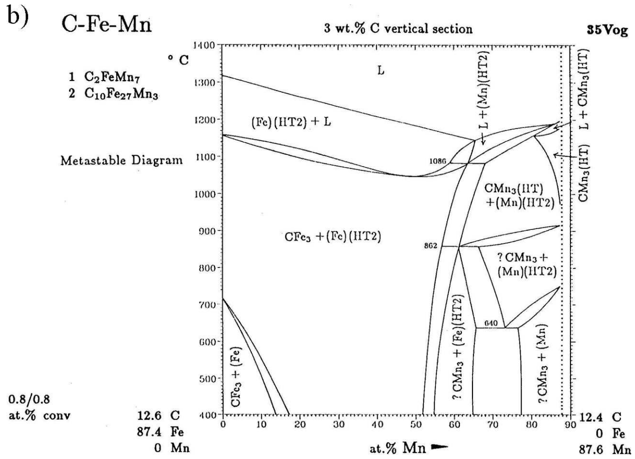


Fig. 1. Metastable diagram a) – C-Fe-Mn, b) –C-Fe-V [18]

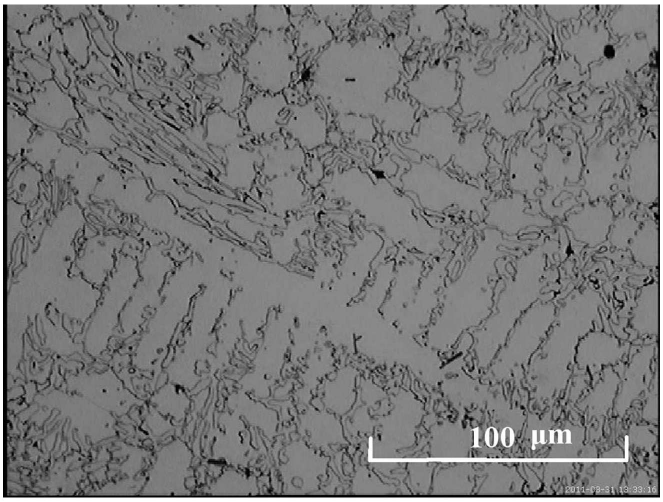


Fig. 2. Primary carbides in the interdendritic spaces of high-alloyed austenite

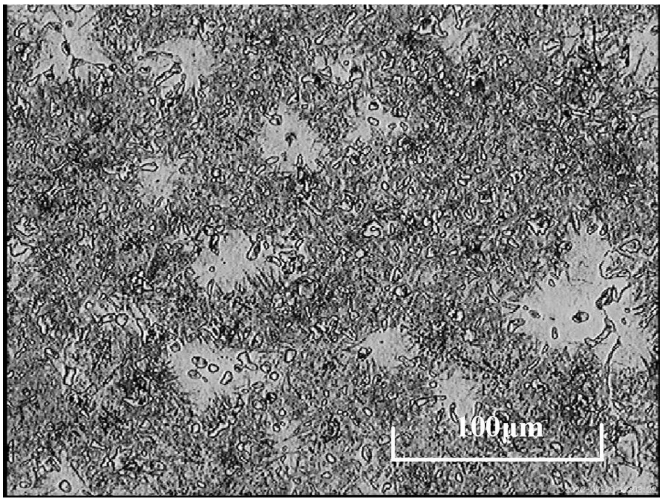


Fig. 3. Cast steel with 2.35% carbon and 6.3% vanadium after heat treatment

In industrial high-speed steels, carbides of the MC-type are mainly formed by vanadium, while secondary carbides are characterised by a high content of V, Mo and Cr [14,20]. Restricting the amount of the tungsten, chromium and molybdenum carbides is associated with the loss of the steel hot workability. In contrast with the brittle γ+M_6C and γ+M_7C_3 eutectic present in the tool steels used so far, the γ+ MC (VC) eutectic is a preferred type of morphology [14], since the share of primary carbides reaches only 20% [15]. This concept was used in, introducing to the regular 18-0-1, 6-5-2, 0-8-2 steel grades increased amounts of vanadium (up to 12%) and carbon (2.3÷2.8%). This resulted in a hardness of 800 HV, due mainly to the presence of primary and secondary vanadium carbides [14,15]. Figure 3 shows the microstructure of the heat treated steel with carbon content of 2.35% and vanadium of 6.3%. Bright primary carbides are visible against the background of martensite and retained austenite. Abrasion tests have shown that steels containing 7 to 12% vanadium occupy an intermediate position somewhere between the G30 sintered carbides (which have the smallest weight loss) and the SW7M and SK10V tool steels used so far [15].

This idea can prove useful when applied to one of the most widely used casting alloys – cast Hadfield steel. Cast Hadfield steel is an alloy known for its excellent abrasive resistance, provided it operates under dynamic loads. When exposed to abrasion under the load-free conditions, e.g. with sand acting as an abrasive, its wear resistance is very poor. Castings made of high-manganese steel are widely used in the power industry and in the materials processing industry for parts of crushers, mills and construction machinery (lining plates, hammers, jaws, cones), owing mainly to their high wear resistance under dynamic loads, while preserving good ductility. Typical heat treatment of castings made of this steel (solution heat treatment in water) eliminates harmful $(Fe,Mn)_3C$ carbides, leading to purely austenitic structure (with a few non-metallic inclusions), as shown in Figures 4 and 5.

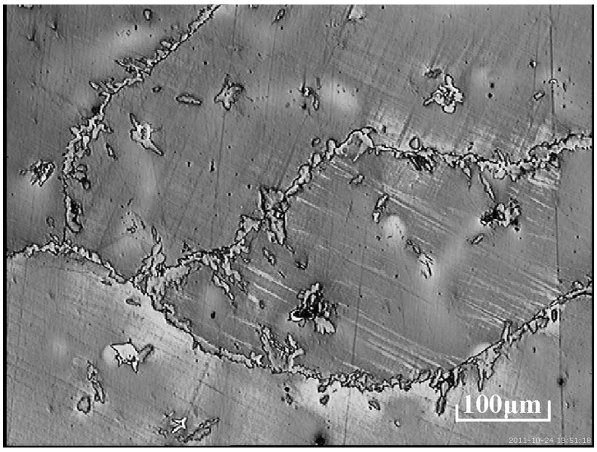


Fig. 4. Hadfield steel in as-cast condition; austenitic matrix with precipitates of acicular alloyed cementite; nital etching

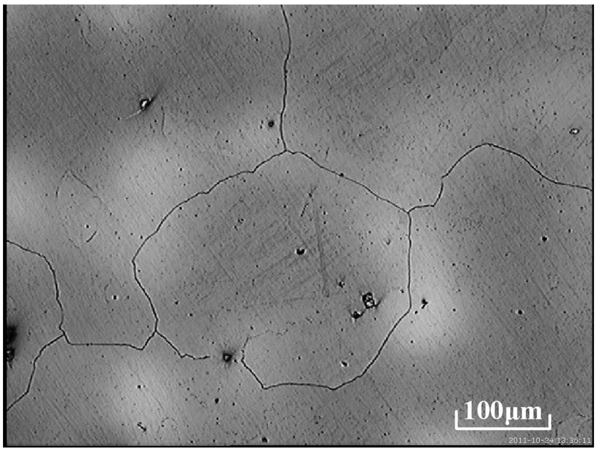


Fig. 5. Cast Hadfield steel after solution heat treatment in water; austenitic matrix free from the precipitates of alloyed cementite at grain boundaries; Nital etching

TABLE 1

Example of the chemical composition of cast austenitic manganese steels [21,22]

Symbol	Chemical composition [wt%]								
	C	Mn	Si	P	S	Cr	Ni	Mo	V
L120G13	0.9÷1.05	11.5÷14	⩽ 1.0	⩽ 0.07	⩽ 0.03	–	–	–	–
	1.12÷1.28	11.5÷14	⩽ 1.0	⩽ 0.07	⩽ 0.03	–	–	–	–
	1÷1.4	12÷14	0.3÷1	⩽ 0.10	⩽ 0.03	⩽ 1.0	⩽ 1.0	–	–
L120G13H	1÷1.4	12÷14	0.3÷1.0	⩽ 0.1	⩽ 0.03	0.6÷1.3	–	–	–
	1.05÷1.35	11.5÷14	⩽ 1.0	⩽ 0.07	⩽ 0.03	1.5÷2.5	–	–	–
	0.7÷1.3	11.5÷14	⩽ 1.0	⩽ 0.07	⩽ 0.03	–	3÷4	–	–
L120G13M	1÷1.4	12÷14	0.3÷1.0	⩽ 0.1	⩽ 0.03	⩽ 1.0	⩽ 1.0	0.1÷0.2	–
	0.7÷1.3	11.5÷14	⩽ 1.0	⩽ 0.07	⩽ 0.03	–	–	0.9÷2.1	–
	1.05÷1.45	11.5÷14	⩽ 1.0	⩽ 0.07	⩽ 0.03	–	–	1.8÷2.1	–
L120G17H	1.3÷1.5	16.5÷19	0.4÷0.8	⩽ 0.08	⩽ 0.04	2÷3	⩽ 0.60	⩽ 0.50	
L240G13V7	2.30	11	0.8	0.08	0.01	0.1	–	–	~6
Chemical composition of cast steel examined by the authors									
L160G10V6	1.65	9.80	1.94	0.038	–	1.66	0.33	0.05	5.5
L240G13V7	2.35	12.1	0.72	0.033	0.016	1.40	–	0.07	6.3
L260G13V9	2.60	14.3	0.75	0.031	0.014	1.41	–	0.07	8.1

Unfortunately, austenite hardness (220÷280HB), which depends on the chemical composition (Table 1) of the steel grade applied for a specific purpose, does not guarantee the required abrasive wear resistance in a metal - non-metal system. Castings for industrial applications are operating as parts of machines that need to be replaced even if suffering a loss of a few millimetres only. Hence, the tendency evolves to keep the casting matrix ductile, while hardening only the surface of the cast element. To achieve this purpose, various grades of the cast high-manganese steel are chosen (Table 1). The surface of the casting is explosively hardened [19], and more recently, following the pattern of (cast) tool steels, vanadium carbides are introduced during the metallurgical process [14,15,20], or SHS synthesis is applied. In the latter case, titanium carbides are produced in liquid alloy under the effect of high temperature developed in this alloy and combined with carbide synthesis [20]. On these methods is largely based modern technology that allows making castings with abrasive wear resistant surface, while preserving the matrix plastic.

3. Test materials and methods

Based on these assumptions, in the authors' own studies, the chemical composition of cast Hadfield steel was modified in such a way as to obtain in the cast alloy after solidification a composite structure consisting of a high-manganese austenitic matrix and fine primary carbides evenly distributed within the whole volume of this matrix. Tests were carried out on a high-manganese steel casting. The steel was produced by melting in an industrial induction furnace the L120G13H cast steel scrap with an addition of Fe-V. This means that the primary vanadium carbides were produced in a metallurgical process when the cast high-manganese steel was melted. The pouring temperature was $T_p = 1550°C$. Samples were taken from castings with the wall thickness of 35 mm, and they served for chemical analysis, microstructure examinations, determination of phase composition, and preparation of specimens for abrasion test. Wear resistance tests were performed in a Miller machine, used to compare the wear resistance behaviour of different structural materials, or of one and the same material subjected to different processes of heat treatment [12]. The test consisted in fixing standard specimens in the grips of the device, applying constant load and subjecting them to the effect of abrasive force of a silicon carbide-water mixture (1:1). Sixteen hour test was run in 4 abrasion cycles. Every four hours the sample was weighed, and based on the weight loss obtained, the wear curves were plotted for the examined specimens. The obtained values of the cast steel wear rate were compared with the wear rate of Hadfield steel specimens of standard chemical composition, subjected to standard heat treatment, i.e. solutionising. Due to similar alloy matrix hardness, the abrasion test was carried out on an alloy containing 5.5% of vanadium.

4. Results

Based on the chemical analysis given in Table 1 it was observed that, compared with standard chemical composition of the cast Hadfield steel, the tested cast steel had a higher content of carbon (from 1.65 to 2.60%), silicon (from 0.72 to 1.94%) and chromium (from 1.40 to 1.66%) with the reduced level of manganese (from 14.30 to 9.80%). The results of examinations carried out by light microscopy have shown that the microstructure of cast steel containing 1.65% carbon and 5.5% vanadium is composed of an austenitic matrix and carbides uniformly distributed therein (Fig. 6). The faceted nature of vanadium carbides (our investigations) indicates that these are the primary carbides formed in the liquid phase. Etching of the structure additionally revealed fine carbides distributed in the entire volume of the melt (Fig. 7). The measured as-cast microhardness of the matrix of the tested steel was comparable with the typical microhardness values obtained for a typical matrix of the cast Hadfield steel (approximately 370μHV), while hardness of the produced carbides was very high, occasionally reaching even the level of 2650μHV.

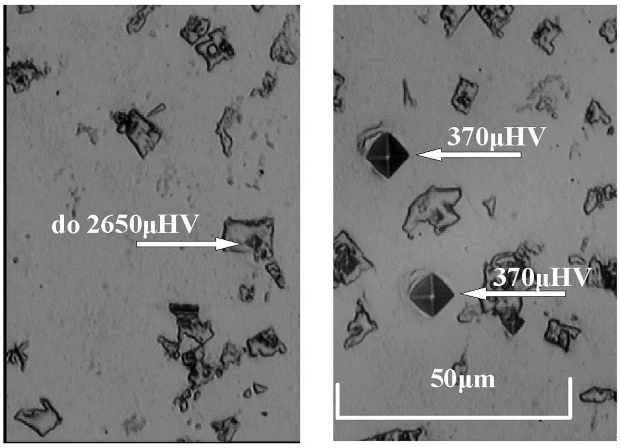


Fig. 6. As-cast microstructure of steel containing 1.65% C and 5.5% V, unetched section (sample L160G10V6, Table 1)

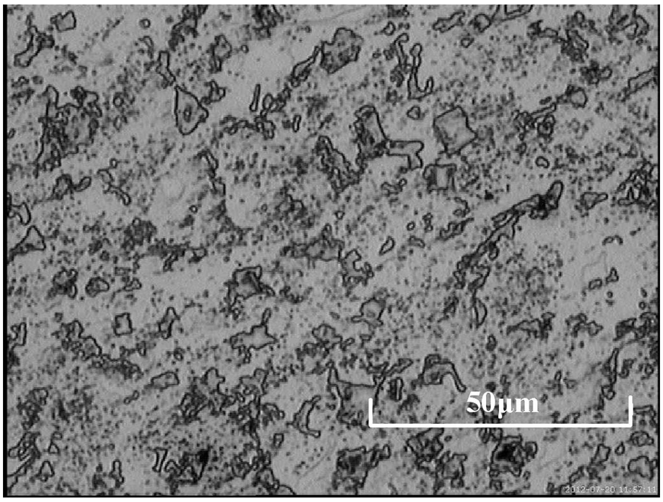


Fig. 7. As-cast microstructure of steel containing 1.65% C and 5.5% V, nital etched (sample L160G10V6, Table 1)

The increase in carbon content (up to 2.35 and 2.60%) and vanadium content (up to 6.3 and 8.1%) has changed the cast steel microstructure. Large, bright primary vanadium carbides and dark acicular martensite appeared and were visible against the background of austenite (Figs. 8 and 9). The microhardness measured in individual microregions amounted to 850μHV in the region of martensite with 8.1% vanadium content, to 900μHV for the vanadium content of 6.3%, and to about 500μHV for both alloys in the regions of retained austenite (Figs. 8 and 9).

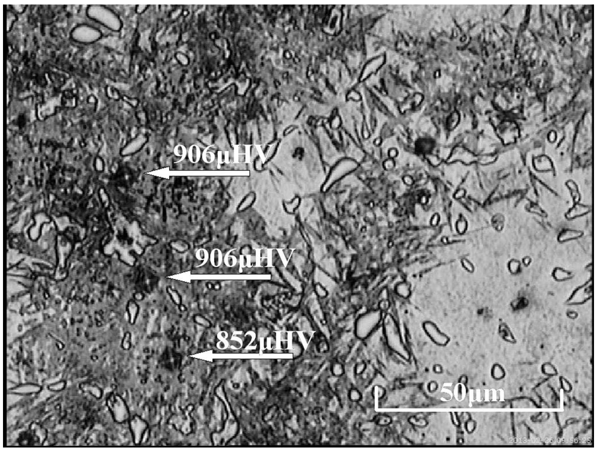


Fig. 8. As-cast microstructure of steel containing 2.35% C and 6.3% V with plotted microhardness of martensite; nital etched (sample L240G13V7, Table 1)

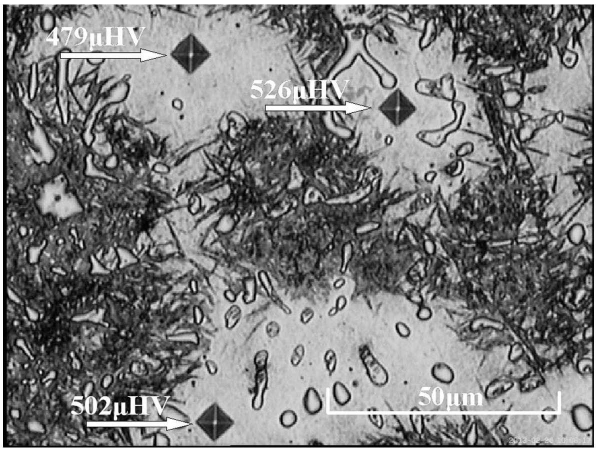


Fig. 9. As-cast microstructure of steel containing 2.6% C and 8.1% V with plotted microhardness of retained austenite, nital etched (sample L260G13V9, Table 1)

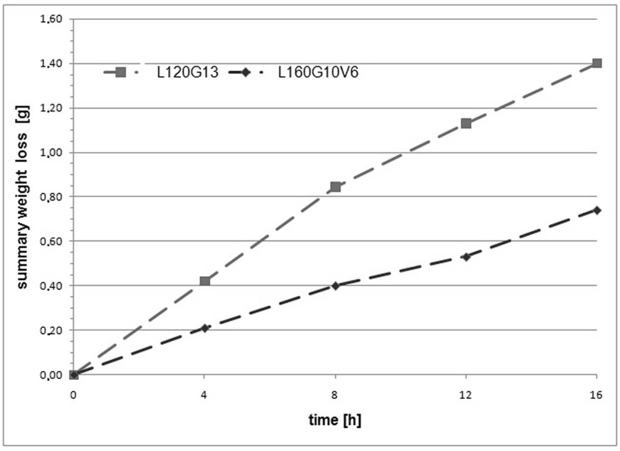


Fig. 10. Wear resistance curves plotted for samples subjected to full abrasion cycle

Based on the results obtained in the abrasion test, it was found that the presence of primary vanadium carbides evenly distributed in the matrix makes the abrasive wear resistance of the alloy with vanadium content of 5.5% double in a metal-non-metal system. The abrasive wear of standard cast Hadfield steel in sixteen-hour test was 1.4 g, while for the cast steel with composite structure the loss amounted to only 0.7 g (Fig. 10).

Differences were also observed in the mere nature of the sample surface wear. In standard cast Hadfield steel, the sample surface wear was even and uniform – the whole surface was smooth, with no major scratches, while surface of the sample containing carbides was worn unevenly – deep scratches were formed on its surface, which means ploughing-type wear. Less advanced degree of wear observed in the examined sample can be attributed to local, uneven wear in the areas where soft austenite was present.

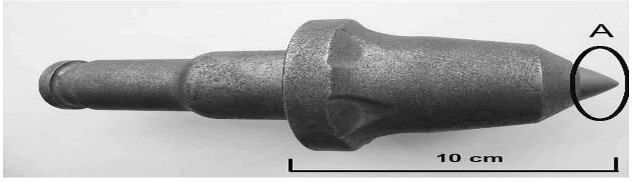


Fig. 11. Schematic design of a handle

Fig. 12. Investment cast tooth from a working part of the holder

The obtained results were referred to industrial castings of crushing elements operating in excavators in the mining industry (Fig. 11). The whole system consists of a handle, made as an element cast from the structural steel (carbon or low-alloyed type) to provide high values of R_m and R_e, with good ductility preserved. The tooth itself (Fig. 12) operates under the conditions of abrasive wear and is additionally subjected to dynamic loads, and therefore the new grade of cast steel with composite structure has been used.

5. Conclusions

The main comments to obtained results are gathered into three groups:

1. Microstructure of the examined cast steel is composed of an austenitic matrix and carbides uniformly distributed in this matrix.
2. The faceted character of vanadium carbides proves that these are the primary carbides formed in the liquid phase.
3. Microhardness of the matrix in the examined cast steel is comparable with the microhardness of the standard cast Hadfield steel matrix.
4. The measured microhardness of the produced carbides can reach even 2650 μHV.
5. The increase in carbon and vanadium content changes the microstructure – needles of martensite appear accompanied by a small amount of retained austenite.
6. Microhardness in the regions of martensite grows up to 900 μHV.
7. The presence of hard vanadium carbides in the matrix doubles the abrasive wear resistance in a metal-non-metal system.
8. Lower wear rate of the cast Hadfield steel with vanadium carbides is due to an uneven nature of the wear, i.e. the ploughing type of wear.
9. The improved abrasive wear resistance creates real chances for the future use of this cast steel in industry.

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