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Increasing the wear resistance of mining machines equipment tools by FCAW with Fe-Mo-Mn-B-C hardfacing alloys

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Abstract:

In this study hardfacing by flux-cored arc welding with Fe-Mo-Mn-B-C-based alloy as an alternative technique for improving wear resistance of mining machines conical picks was investigated. The microstructure of hardfaced layer consists of the uniformly distributed faceted grains of binary $(Fe,Mn)Mo_2B_2$ boride phase with average size of 25 μm and austenite-based eutectic. The hardness measured by microindentation and microscratching techniques across the interfaces between deposited layer and base steel was within 2.2 – 18 GPa. No welding defects such as cracks, pores or non-metal inclusions in the hardfaced layer and heat affected zones were detected. Comparative studies of the developed hardfacing alloy with commercially available Capilla HR MAG hardfacing and heat treated 35HGS steel were carried out using testing machine developed at the department of machinery engineering and transport of AGH university of science and technology for semi-industrial wear tests of mining machines conical picks. Wear measurement results show that using hardfacing with proposed alloy of Fe-Mo-Mn-B-C system leads to decreasing of impact-abrasion wear rate in approximately 3 times than that for tested commercial materials. This allows to recommend hardfacing by FCAW with proposed material in form of flux-cored wire for conical picks insert holders' surfaces during mining of hard rocks.

Keywords: hardfacing, iron-molybdenum boride, impact-wear resistance, manganese austenite, mining tools

1. Introduction

Milling heads of the mining machines in many cases are equipped with a conical cutting picks consisting of a steel holder part and cemented carbide (usually WC) insert. Due to high rates of impact-abrasion wear, occurring during underground excavation and fragmentation of hard rocks or coal, the durability of cutting picks remains very low. In some cases, conical picks need to be replaced with a new ones, even after several hours of mining operations [1]. Considering recent increasing trends in tungsten raw materials pricing, such low operational conditions of conical picks need significant additional costs. Analysis of the recent progress in WC-based cemented carbide development [2, 3] allows to conclude that the most desirable relationships between its hardness toughness and strength are almost reached, so they might be improved only within a narrow range by grain refinement, improving sintering techniques, binder alloying, etc. Besides, the pick inserts materials for different working environments only limited by WC-Co cemented carbides of B1, B2, B20, B23, G15 and similar grades are suitable [4, 5] for the pick's inserts. Moreover, in many cases cemented carbide inserts might be chipped out from the holder into the working zone due to the low abrasion resistance of the insert holder cylindrical and conical surfaces. The most widely used insert holders' materials are low alloyed mild carbon heat treated steels of GOST grades 40H, 40HN, 36HNM or 35HGS. So, the maximum surface hardness of the sample holder is about 45 HRC, cannot provide sufficient protection against abrasion wear, especially in aggressive abrasive environments with high particles microcutting ability. For these reasons, many investigations aimed at surface engineering technologies of increasing hardness and wear resistance, including laser cladding, physical vapor deposition (PVD) [3, 6, 7], hardfacing with rod electrodes and flux-cored wires (FCAW) [8, 9]. Using of hardfacing processes allows to obtain multilayered coatings with thickness up to 3-5 mm and hardness within 55 – 65 HRC. However, the most widely used commercial hardfacing electrodes are the high-chromium hypereutectic alloys with high amount of coarse-grained M_7C_3 – type carbides, characterized by very limited resistance at the impact loads due to low fracture toughness [10, 11]. Therefore, development of a new hardfacing materials with increased resistance to impact wear together with high resistance to abrasion is an important direction in improving durability of conical picks. The promising hardfacings for such purpose are the electrode materials based on Fe-Mo-B-C alloying system [9, 12], where *in situ* formation of $FeMo_2B_2$ hard phases in form of faceted uniformly distributed grains occurs, as a result of chemical reaction in electrode flux. It is expected that extension Fe-Mo-B-C system by Mn addition can provide formation of manganese austenite, exhibiting ability to deformation hardening during impact.

The present research aimed at development of a new Fe-Mo-Mn-B-C-based alloying system for FCAW hardfacing of conical picks used in mining machines as well as evaluation the impact-abrasion wear behavior of hardfacing deposits in comparison with commercially available hardfacings and materials.

2. Materials and Methods

Flux-cored wires for hardfacing were prepared by drawing the dried mixture of commercial available Mo powder of MPCh grade with average particle size of 5 μm, boron carbide (brand 2V ISO 9001:2008), ferrosillicomanganese (grade MNS17) and arc protection components into the low carbon steel sheath. The cross-section of resultant flux-cored wires was equal to 8×2.5 mm^2. Samples for investigations were prepared by arc hardfacing in two layers on the mild carbon steel (St.3) substrate in flat position at the following welding parameters: current 180 A, voltage 34-36 V and reverse polarity. The samples with dimensions of 10×20×40 mm were cut from hardfaced plate for hardness measurement, wear resistance investigation, macro- and microstructure observations. Microstructure was examined by means of scanning electron microscopy adjusted in backscattered electron diffraction mode using ZeiSS EVO 40 XVP electron microscope. Average values of grain size were measured by random intersections technique for at least 50 randomly chosen grains. Qualitative and quantitative determination of the chemical composition at the hardfaced layers was examined by energy-dispersive X-ray spectroscopy (EDS) technique. Scratch tests across the "deposition − base

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metal" interface and heat affected zones were carried out using diamond Vickers indenter (pyramid) by "edge ahead" scheme and PMT3M microhardness tester. According to GOST 21318-75 the scratch hardness (Hs) was calculated by following formula:

$$H_S = \frac{3.782 \cdot F}{b^2}, \tag{1}$$

where F is the normal force acting on the indenter (kgf); b is the track width (mm^2) after scratching. The apllied force during microindentation and microscratching tests was set to 0.1 kgf.

The typical chemical composition and hardness of the top hardfaced layer with the experimental harfacing alloy (EPM2), commercial hardfacing of the Capilla brand (Germany) and commercial heat treated mild carbon steel can be seen in Table 1.

Table 1. Characteristics of the conical picks insert holders used for comparative study

Sample	Chemical composition, wt. %								Hardness, HRC
	Fe	Mo	Cr	Mn	B	C	Si	WxCy	
EPM2	Balance	29	-	6.7	3.4	1.1	1	-	62
Commercial steel, 35HGS	Balance	0.1	1.2	1	-	0.35	1.2	-	54
Commercial hardfacing, Capilla HR MAG	Balance	-	-	0.1	-	0.05	0.3	50	55

To perform wear tests in conditions which is close to the real mining processes hardfaced conical picks as well as the serial ones were tested using semi-industrial testing machine (Fig. 1), developed at the department of machinery engineering and transport of AGH university of science and technology [8]. Four conical picks samples of each type were located at different angles with respect to the monolithic abrasive block surface providing different degrees of interaction with abrasive environment.

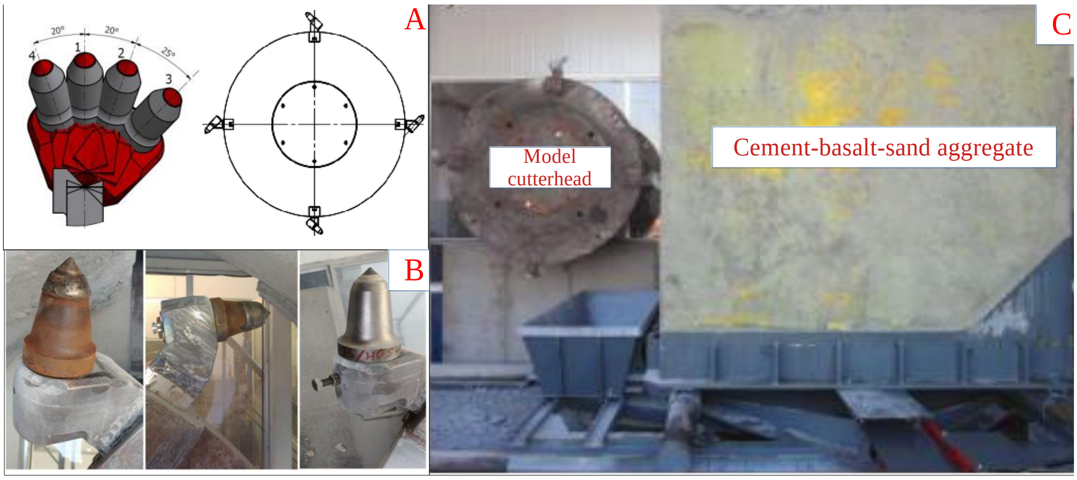

Fig. 1. Experimental conical picks testing [8]:
A – relative positioning of the conical picks samples in the model cutterhead,
B – fixed conical picks of different types, C – general view of the testing machine

Wear tests were performed at the main following parameters: cutterhead rotational speed – 42 rpm, cutting speed – 0.05 m/min, cutting distance – 50 mm, worn abrasive volume per set of picks – 0.5 m^3. The wear resistance of the samples was determined by measuring mass loss using analytical axis with measurement accuracy within 0.01 g. Hardfaced layers were deposited on the conical surfaces near the

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cemented carbide tips along the annular trajectories and in the form of longitudinal parallel layers (Fig. 2).

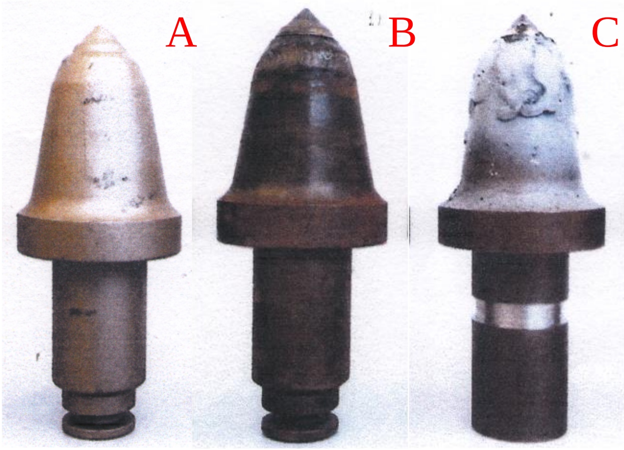

Fig. 2. The general view of tested conical picks: A – heat treated steel of 35HGS grade, B − Capilla HR MAG hardfacing, C – EPM2 hardfacing of Fe-Mo-Mn-B-C system

3. Results

Resulting microstructure of the EPM2 hardfaced top layers (Fig. 3, A) consists of faceted sharp-edged grains of refractory superhard (Fe,Mn)Mo_2B_2 phase which are uniformly distributed in matrix metal represented by fine dispersed plate-like austenite + (Fe,Mn)Mo_2B_2 eutectic. The average size of binary boride reinforcements is about 25 μm and its total amount is approximately 30% by volume. Microstructural observations of the regions at the interfaces between hardfaced coating and base steel (Fig. 3, B) show the presence of significantly finer microstructure, where (Fe,Mn)Mo_2B_2 grains with size within 1-2 μm acts as nucleation cores for eutectic formation. In the normal direction to a visible boundary between coating and base metal, there are columnar austenite grains with dendrite structure which are typical for welding joints obtained using electrodes of austenite type. No welding defects such as macropores, cracks, non-metal (slag) inclusions, delamination etc., were detected along the interface, indicating the strong metallurgical bonding between deposition and base metal. The microindentation tests show that hardness of hardfaced layer is within 11.5 – 18 GPa, while base metal remains relatively soft (tough) having hardness of 250 HV.

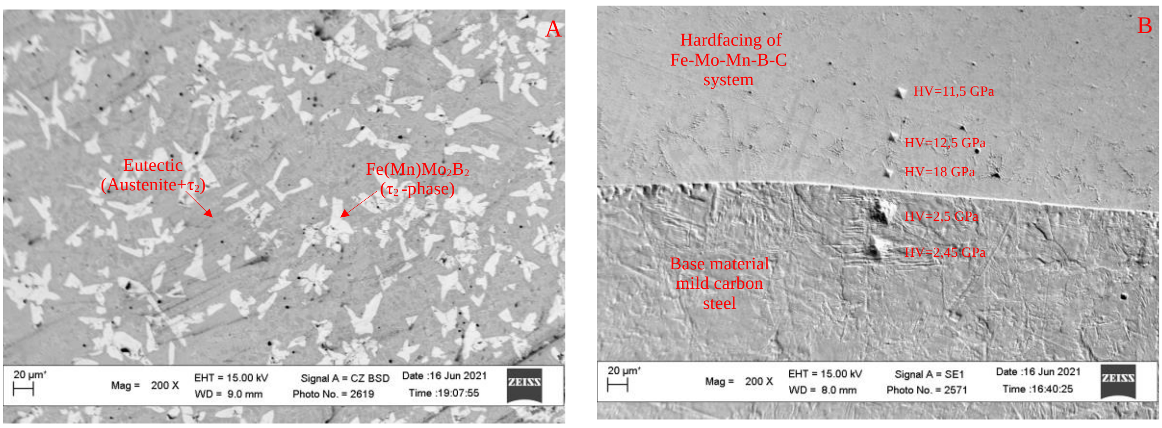

Fig. 3. Microstructures of the investigated EPM2 hardfacing alloy:
A − microstructure of the top layer, B − microstructure of the harfacing – base metal interface and related microhardness tests results

The results of microscratching tests performed in the normal direction to the coating – base metal interface (Fig. 4) show that transition zone has relatively low length (60 μm), where hardness smoothly increases from 2 to 12 GPa. The next narrow characteristic zone with length of 40 μm has the highest hardness (12 GPa), which is probably caused by significant structure refinement by high solidification speed due to significant temperature gradient. The scratch hardness in next region, corresponding to the main amout of deposited alloy remains practically unchangeable within 10-11 GPa on the rest cross-sectional area.

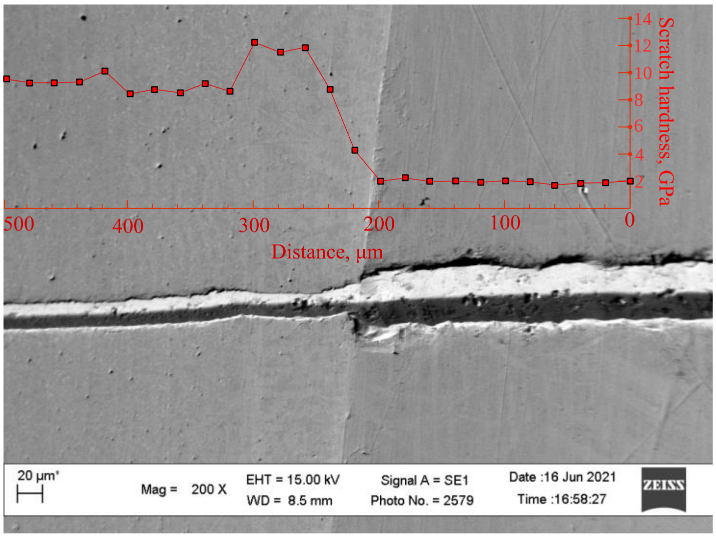

Fig. 4. Results of scratch tests of the EPM2 hardfacing

Wear resistance tests results performed using hardfaced and serial conical picks are shown in Fig. 5. As can be seen from figure the most difficult working conditions of interaction with a abrasive block is observed for conical picks placed in position № 2. These samples exhibit highest wear rate measured by mass loss for all investigated materials. However, the value of wear resistance for the experimental hardfacing EPM2 of a Fe-Mn-Mo-B-C system is almost in 2.75 and 3.75 times higher than that for Capilla HR MAG hardfacing and heat treated commercial 30HGS steel, respectively. It should be noted, that wear rate of commercial materials tested in other positions (№1, №3 and №4) are similar and lower by 10-20%, while the wear rate of EPM2 hardfacing in position № 1 is almost equal to that in position № 2. Despite this, experimental hardfacing still shows lowest wear rate among all investigated materials.

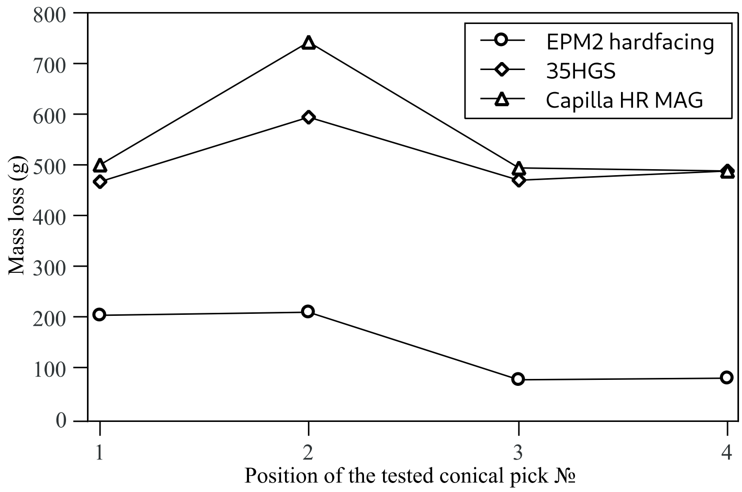

Fig. 5. Relationship between position of conical picks and its wear resistance for different tested materials

4. Discussion

The analysis of the microstructure of the experimental hardfacing of the Fe-Mo-Mn-B-C system allows to classify the type of obtained alloy as hypereutectic boride-austenitic. In contrast with the most widespread hypereutectic high-chromium hardfacing alloys the morphology of the reinforcing phase is much closer to the equiaxial form providing higher resistance to impact and cyclic loads. However, hardness of the $Fe(MoB)_2$ complex boride phase is more than 25 GPa which is in two times higher than for M_7C_3-type chromium enriched carbide and close to the mixture eutectic tungsten carbides. The further increasing of the hardness for the $Fe(MoB)_2$ might be reached by partial dissolution of the Mn in crystal lattice sites occupied by Fe. Another important role of Mn in the alloy is the promoting of stable austenite phase formation, with high deformation hardening ability. In the given case such high-manganese austenite phase allocated in form of thin layers in eutectic colonies with boride phase, providing resistance to crack propagation.

It is important to note that there is no direct relationship between hardness and wear resistance under impact-wear conditions. So, both the structure morphology features and phases mechanical properties are proved to perform the key role in resistance to impact-abrasion wear. According to this viewpoint, the *in situ* formed, during arc hardfacing, complex superhard refractory boride phases is sufficient to improve the wear resistance.

5. Conclusions

The development of new hardfacing material of a Fe-Mo-Mn-B-C system for the improving impact-wear resistance of mining machines conical picks has been studied. It was shown that componets of a given alloying system used in flux-cored wires allows to obtain coatings with high microhardness due to the *in situ* formation of complex refractory borides of $(Fe,Mn)(Mo,B)_2$ acting as reinforcements in hypereutectic austenite-boride alloys. The semi-industrial tests show that such type of alloys can be suitable for practical using, because of their impact-abrasion wear resistance, which is higher than that for tested commercial tungsten enriched hardfacing and serial heat treated steel in 2.75 and 3.75 times, respectively. The further investigations are planned to be aimed on automation of hardfacing processes within given alloying system to reach higher deposition productivity and accurate layers geometry.

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