FORMATION OF THE INCREASED WEAR-RESISTANT PROPERTIES OF HARDOX 450 STEEL BY DEPOSITED COATINGS

S V Konovalov¹, V E Kormyshev¹, E V Kapralov¹, Y F Ivanov², O V Zavatski¹ and V E Gromov¹

¹ Department of Physics n.a. Prof. V.M. Finkel, Siberian State Industrial University, 42 Kirova Street, Novokuznetsk, 654007, Russia
² Institute of High Current Electronics, Siberian Brunch of the Russian Academy of Sciences, 2/3 Akademichesky Ave, Tomsk, 634055, Russia

E-mail: konovserg@gmail.com

Abstract. The structure-phase conditions formed during the deposition of surface coatings on Hardox 450 steel by the wire comprising C, V, Cr, Nb, W were examined by the methods of X-ray phase analysis and transmission electron diffraction microscopy. It was established that after the hardened layer was deposited, the wear-resistance increased 153 times and the coefficient of friction in the material decreased 2.5 times. It was concluded that the increased properties of the surface coating were due to the formation of martensitic structure and the occurrence of high volume fraction of carbide phase inclusions.

1. Introduction
Problems of surface restoration and hardening of machine and mechanism elements appeared when the mechanical engineering became one of the basic branches of industrial production and continue to be relevant nowadays.

Among the technologies of restoration and deposition of hardening coatings the leading position belongs to the arc surfacing method due to the deposition of coatings on the surfaces of large scale equipment operating under conditions of abrasive wear. For example, on the components of groundcare, construction and mining equipment. In these cases the choice of the arc surfacing method is conditioned not only by the possibility of deposition volume coatings, up to several millimeters of thickness, but also the possibility of formation of high-strength and wear-resistant structures in the surface coating by adjusting the composition of the deposited electrode. Thus, there is a specific interest in application of powder electrodes (wires) for deposition of coatings with the desired physical and strength properties, which allow the phase composition of the deposited material to be varied greatly by combining the powder components during the electrode production [1-9].

In our earlier works [10, 11] we studied the features of structure formation and properties of wear-resistant coatings deposited on Hardox 400 steel under conditions of strengthening particles synthesis from the components of flux-cored wires, including the coatings deposited by the flux-cored wires containing carbide- and boride-forming metals, carbon and boron in the structure-free state that ensure the formation of a coating structure with high operational properties.
The aim of this work is to expand the research and to conduct the metallographic analysis of the impact of deposition by the flux-cored wire containing C, V, Cr, Nb, W on the martensitic steel Hardox 450 and on the change in structure and properties of the formed coating.

2. Materials and methods

Hardox 450 steel ((weight %): 0.19-0.26% C; 0.70% Si; 1.6% Mn; 0.025% P; 0.010% S; 0.25% Cr; 0.25% Ni; 0.25% Mo, 0.004% B; the rest – Fe) was used as a base material. As well as Hardox 400 steel, Hardox 450 steel is intended for conditions under which special requirements for wear-resistance alongside with good cold bending properties and weldability are imposed. Field of application for Hardox 450: dump truck bodies, containers, crushers, screeners, feeders, skip winders, knife cutting edges, conveyors, buckets, knives, gears, sprockets, etc. [12].

The coatings were deposited by the flux-cored wire, having the following chemical composition: (weight %): 1.4% C; 1.0% V; 7.0% Cr; 8.0% Nb; 1.2% W; the rest – Fe. Single- and double-layer coatings were applied. Double-layer coating was carried out perpendicularly to the single-layer coating. The coating was deposited in the shielding gas, having the chemical composition: Ar 82%, CO₂ 18% with arc current 250 – 300 A and arc volts 30 – 35 V.

The studies of the phase composition and defect substructure of steel and deposited metal were carried out by the methods of X-ray structure analysis and transmission electron diffraction microscopy. The foils were produced by the method of electrolytic thinning of plates cut from the deposited metal (layer located at half the thickness of the deposited metal), contact zone of the deposited metal and the steel at a distance of 15 mm from the contact zone in the volume of the steel sample.

3. Results and discussion

Microhardness analysis along the cross-section of the formed coating after single-layer deposition revealed the following. The maximum value of microhardness 11 GPa is observed in the layer with 5 mm of thickness near the surface. Then it non-monotonically decreases and constitutes 6.5 GPa in the base material. Thus, the deposition of coating leads to an almost two-fold increase in microhardness. Formation of the second deposited layer results in the increase of microhardness up to 12.5 GPa. This value is observed in the layer of approximately 1 mm thickness. As the distance from it increases the microhardness (at a distance of 2.5-3.5 mm) decreases up to 7 GPa with its further increase to maximal values 10 GPa at a distance of 4.5-5.5 mm. Then microhardness decreases to values of the base material. Apparently, sharp decrease in microhardness is connected with the contact zone of single- and repeated-metal deposition.

Analysis of tribological tests showed the following. If the wear performance of material is 95.10*10⁻⁶ mm³/N·m, then after a single deposition – 0.69*10⁻⁶ mm³/N·m, and after a double deposition – 0.62*10⁻⁶ mm³/N·m. Consequently, deposition leads to the increase of wear resistance in 153 times after a double deposition and in 138 times after a single one. In its turn, the coefficient of friction of the base material is 0.259, of the single deposited material is 0.104, and of the repeatedly deposited material is 0.132, i.e. it decreases by almost 2.5 times.

The specified increased strength and tribological properties of the deposited metal are conditioned by the state of the material structure, namely, its phase composition and the state of the defect substructure.

By the methods of X-ray structural analysis it was found that material of a single deposition contains the following phases: α-Fe – 63.2%, Fe₃O₄ – 28.8%, Fe₃C – 6.0%, CrC – 2.0%; double deposition: M₆C₆ – 52.3%, α-Fe – 46.7%, Nb₆C₃ 1.0% (in wt.%). Thus, in the material of single and double deposition a multiphase structure is formed. The basic phase (excluding α-phase) in the single deposition is iron oxide of Fe₂O₃ composition. The basic phase of the repeatedly deposited coating are carbides based on the special elements (carbides Nb, W and Cr). Formation of the double deposition leads to a substantial increase in the volume fraction of carbide phase and the complete absence of oxide phase.
To establish the factors responsible for the increased properties by the methods of transmission diffraction electron microscopy the analysis of the defect substructure of base material and deposition was carried out.

Studies of the base material revealed the structure, which was formed as a result of quenching and subsequent tempering of steel (tempering of martensite) (Figure 1). Fragmented crystals of lamellar morphology, formed during the martensitic transformation, were found in the \( \alpha \)-phase grains. Particles of carbide phase are found in the volume and along the boundaries of crystals.

Structure of subgrain type is found more rarely, the typical image of which is given in Figure 2.

![Figure 1. Electron microscope image of the structure of Hardox 450 steel.](image1)

![Figure 2. Structure of the subgrain type in Hardox 450 steel.](image2)

The structure of the metal contact zone of the deposited coating and the basic material shares many similar characteristics with the structure of the initial steel. Martensitic structure is revealed. In its crystals the dislocation substructure in the form of randomly distributed dislocations and dislocation tangles can be seen (Figure 3).

![Figure 3. Randomly distributed dislocations and dislocation tangles formed in the structure of \( \alpha \)-phase of the contact zone of deposition and base metal.](image3)

The typical electron microscope images of the structure of the repeatedly applied coating are presented in Figure 4. It can be seen that the formed material is multiphase. In Figure 4a the inclusions of submicron size, which are difficult to electrolytically polish, are indicated by arrows. The results of the X-ray phase analysis show that these inclusions belong to the carbide phase (carbides of the composition \( \text{M}_{23}\text{C}_6 \) ((Cr, Fe, W)\(_{23}\)C\(_6\))). The other phase is well polished and obviously is a solid solution on the basis of \( \alpha \)-Fe (Figure 4b).
The characteristic electron microscope image of the structure of $\alpha$-phase of the repeated deposition is given in Figure 5. The lamellar structure formed as an effect of martensitic transformation is clearly visible.

The dislocation substructure in the shape of polydimensional networks is found in the crystals of martensite (Figure 6a). In some cases transformation twins are founded in the volume of martensite crystals (Figure 6b). Niobium carbide NbC nanoparticles of the second phase – are found inside and on the boundaries of martensite crystals.
4. Conclusions
The research of the phase composition, defect substructure, tribological properties and microhardness of the singular and double coating deposited on the steel by C, V, Cr, Nb, W wire is carried out. It is shown that wear resistance of the deposited metal is about 153 times higher compared to Hardox 450 wear resistance; coefficient of friction of the deposited metal is 2.5 times lower than the steel friction coefficient. It is shown that formation of the second deposited coating does not have a great influence on the tribological characteristics of the material. It is found that the increased mechanical and tribological properties of the deposited layer are conditioned by formation of a multiphase submicron and nano-dimensional structure. The hardening of this structure is associated with the formation of a martensite structure of $\alpha$-matrix and the presence of high (more than 50%) volume fraction of carbide phase impurities based on Fe, Cr, W and Nb.

5. Acknowledgements
The research was performed under the grant of the Russian Science Foundation (project No. 15-19-00065).

6. References
[1] D’Ans, Pierre and Degrez Marc 2015 *Surface and Coatings Technology* **276** 349–359
[2] Yang Xincheng, Ma Xiaolong, Moering Jordan, Zhou Hao, Wang Wei, Gong Yulan, Tao Jingmei, Zhu Yuntian and Zhu Xinkun 2015 *Materials Science and Engineering: A* **645** 280–285
[3] Rao Lei, Wang Shuang-jun, Zhao Jian-hua, Geng Mao-peng and Ding Gang 2011 *J. of Iron and Steel Research, International* **21** 869–877
[4] Słoma J, Szczygieł I and Sachajdak A 2011 *Archives of Civil and Mechanical Engineering* **11** (2) 437–449
[5] Chen Xizhang, Yuan Qibing, Madigan Bruce and Xue Wei 2015 *Corrosion Science* **96** 178–185
[6] Chen Xizhang, Shen Zheng, Chen Xing, Yucheng and Huang Quining 2011 *Fusion Engineering and Design* **86** 2943–48
[7] Chen Xizhang, Fang Yuanyuan, Li Peng et al 2015 *Materials & Design* **65** 1214–21
[8] Yilbas, Bekir Sami et al 2013 *Laser Surface Processing and Model Studies* (Berlin: Springer)
[9] Senthilkumara B and Kannanb T 2015 *Measurement* **62** 127–136
[10] Kapralov E V, Budovskikh E A, Gromov V E and Ivanov Yu F 2015 *Russian Physics Journal* **58** (4) 471–477
[11] Kapralov E V, Raykov S V, Budovskikh E A, Gromov V E, Vashchuk E S and Ivanov Yu F 2014 *Bulletin of the Russian Academy of Sciences: Physics* **78** (10) 1015–21
[12] Grnezh B 2008 Mining **3** (79) 34–38
[13] Zuev L B, Danilov V I et al 2009 *Physics of the Solid State* **51** (6) 1137–41
[14] Olesyuk O V, Konovalov S V and Romanov D A 2014 *Modern problems of science and education* **2** 85