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МИКРОСТРУКТУРА И ТРИБОЛОГИЧЕСКИЕ СВОЙСТВА ПОВЕРХНОСТИ СТАЛИ ХАРДОКС 450, МОДИФИЦИРОВАННОЙ НАПЛАВКОЙ ПОРОШКОВОЙ ПРОВОЛОКОЙ Fe-C-Cr-Nb-W И ЭЛЕКТРОННО-ПУЧКОВОЙ ОБРАБОТКОЙ

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Аннотация: *Исследованы структурно-фазовые состояния и трибологические свойства покрытия, наплавленного на мартенситную низкоуглеродистую сталь Hardox450 порошковой проволокой Fe-C-Cr-Nb-W и модифицированного последующей электронно-пучковой обработкой. Показано, что электронно-пучковая обработка наплавленного слоя толщиной ~ 5 мм приводит к формированию модифицированного поверхностного слоя толщиной ~ 20 мкм, основными фазами которого являются α-Fe и карбиды NbC, Fe_3C и $M6C(Fe_3W_3C)$, морфология и размеры которых отличаются от необработанного слоя наплавки. Отмечено, что наблюдаемая в эксперименте малая величина параметра кристаллической решетки NbC может быть обусловлена высоким уровнем концентрации вакантных междоузлий, имеющих меньший размер по сравнению с заполненными междоузлиями. Установлено, что износостойкость наплавленного слоя после электронно-пучковой обработки возрастает более чем в 70 раз по отношению к износостойкости стали Hardox450, а коэффициент трения снижается ~ в 3 раза.*

Ключевые слова: *структура, фазовый состав, наплавка, электронно-лучевая обработка, морфология, карбиды, трибологические свойства.*

MICROSTRUCTURE AND WEAR PROPERTIES OF HARDOX 450 STEEL SURFACE MODIFIED BY FE-C-CR-NB-W POWDER WIRE SURFACING AND ELECTRON BEAM TREATMENT

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Abstract: *Structural phase states and tribological properties of the coating surfaced onto Hardox 450 martensite low-carbon steel with powder wire Fe-C-Cr-Nb-W and modified by subsequent electron-beam processing are studied by methods of modern physical material science. It is shown that irradiation of ~ 5 mm thick surfaced layer with high intensity pulsed electron beams results in the formation of ~ 20 μm thick surface layer with the master phases of α-Fe and NbC, Fe_3C and $M_6C(Fe_3W_3C)$ carbides. It is established that wear resistance of the surfaced layer after electron-beam processing increases more than 70-fold relative to wear resistance of Hardox 450 steel and friction coefficient decreases significantly (~3-fold).*

Key words: *structure, phase composition, surfacing, electron-beam processing, morphology, carbides, tribology properties.*

Introduction

The important fundamental task is to obtain the coatings with high service properties ensuring the increase in operational life of products in the extreme conditions of high wear, corrosion, mechanical loads and temperatures [1]. Hardfacing using superior material coatings has been widely used to achieve longer service life [2-5]. Among different methods welding is considered as an economical choice as a variety of process can be utilized to deposit a desired coating [6].

Thorough analysis of «wear parameters – hardness microstructure» relation is necessary in research and practical application of surfacing of various types in the critical components and products [7-10]. Only in this case it is possible to obtain products with high operational parameters.

The purpose of the research is the analysis of structure and tribological properties of the layer formed on Hardox 450 steel with electrocontact surfacing of Fe-C-Cr-Nb-W wire and modified by high intensity pulsed electron beam irradiation.

Material and methods

Hardox 450 steel (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; balance – Fe, weight %) was used as a base material. The surfacing of the strengthening layer was done by with consumable metal electrode shielded by inert/active gas with automatic feeding of filler wire) inert gas shielded welding (Ar – 98%, CO_2 – 2%), under welding current 250-300 A and voltage 30-35 V. The powder wire 1.6 mm in diameter of the following chemical composition (weight %): 1.3 C; 7.0 Cr; 8.5 Nb; 1.4 W; 0.9 Mn; 1.1 Si; balance – Fe was used as surfaced electrode. Surfacing results in the formation of high strength surface layer ~ 5 mm in thickness.

Modification of the surfaced layer for increasing in its tribological properties was done by surface irradiation with intensity electron beam at the facility «SOLO» [11] in the regime of meting and high speed crystallization. Electron-beam processing was done in two stages: parameters of electron beam at the first stage – density of electron beam energy in pulse $E_s = 30$ J/sm^2; pulse duration $\tau = 200$ μs; quantity of pulses $N = 20$; at the second stage – $E_s = 30$ J/cm^2; $\tau = 50$ μs; $N = 1$. The irradiation regimes were chosen by calculation results of temperature field forming in the surface layer of the material in irradiation align in one pulse regime [12]. Investigations of tribological properties, defect substructure, chemical and phase composition of modified surface layer are carried out using the methods of modern material science.

Results and Discussion

The irradiation of the surfaced layer with high intensity pulsed electron beam results in the formation of the modified surface layer up to 20 μm thick. The modified layer differs from the major volume of the surfaced material by the degree of structure dispersion revealed in ion etching of the transverse metallographic section.

In the volume of the surfaced layer unirradiated with electron beam the dimensions of the etched structural elements reach 1.5 μm, and after electron-beam processing dimensions of etching elements (evidently, high melting compounds possessing a comparatively low level of etching with ion beam) vary within 150-750 nm (Fig. 1).

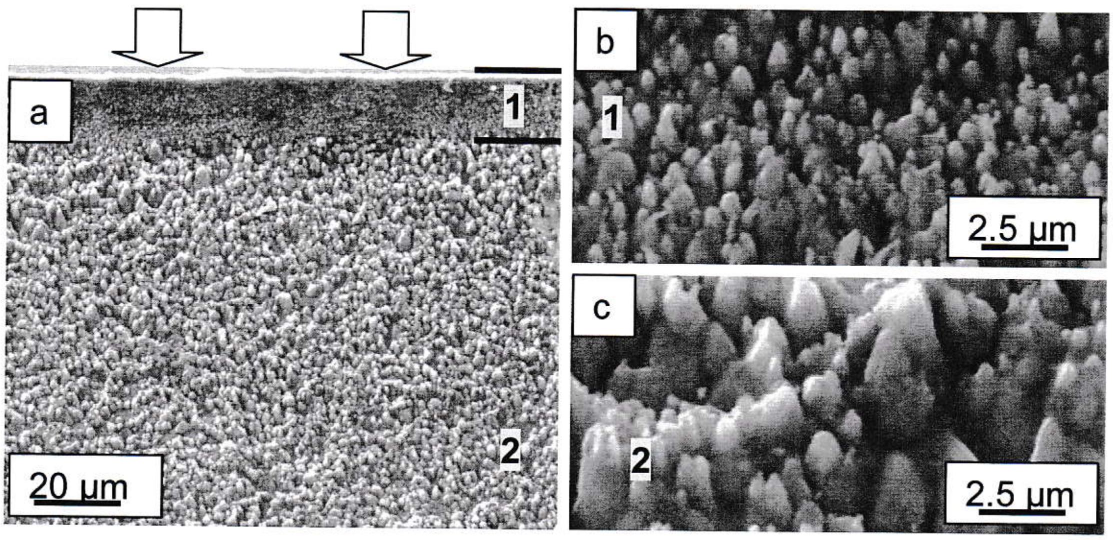

Figure 1 - Structure of the surface layer. The transverse etched metallographic section. The arrows designate the irradiation surface of the layer with pulsed electron beams. Figures designate: 1 – the layer modified with electron-beam processing; 2 – the main volume of the surfacing

When analyzing the results of X-ray phase analysis shown in Fig. 2 and in Table 1 it can be revealed that the master phases of the studied surface layer of the surfacing are α-Fe (solution of Fe based bcc lattice) and niobium carbide NbC. A comparatively small parameter of crystal lattice of niobium carbide engages the attention. The niobium carbide NbC has a parameter of crystal lattice within 0.4429 to 0.4471 nm [13].

A comparatively small value of crystal lattice parameter of niobium carbide observed by us in the experiment (Table 1) may be caused by a high level of concentration of vacant interstitial sites having the smaller linear dimension compared to the occupied interstitial sites. It is confirmed by the results of experimental works [14, 15].

Table 1 - Results of X-ray phase analysis of the surfaced layer after the processing with intense pulsed electron beams.

Revealed phases	Phase content, mass. %	Lattice parameters, a, nm	Dimension of coherent scattering region, nm	$\Delta d/d*10^{-3}$
α-Fe	46.9	0.28553	61.8	2.36
NbC	53.1	0.43691	12.7	6.47

TEM image analysis shows that the second phase inclusions are located largely along the grain boundaries in the form of extended interlayers 100-150 nm in thickness. The second phase inclusions located in the grain junctions have the shape of the extended triple node and dimensions of such inclusions reach 1 μm.

Using the methods of microdiffraction analysis with dark field technique it is shown that the second phase inclusions located along grain boundaries in the form of interlayers are carbide $M_6C(Fe_3W_3C)$. In the volume and along the boundaries of martensite crystals the particles of iron carbide Fe_3C (possibly, M_3C) are revealed.

The surface layer structure of the surfacing irradiated with intense pulsed electron beams is characterized by the presence of the facet shape inclusions located chaotically in the grain volume (Fig. 2). The dimensions of such inclusions reach 2 μm. Indexing of microelectron diffraction pattern obtained from such inclusions is indicative of their being niobium carbide NbC.

Thus, by methods of electron diffraction microscopy it is shown that the surface layer of the surfacing modified with intense pulsed electron beam is a multi-phase aggregate with the master phases of α-iron based solid solution and carbides M_6C, NbC and Fe_3C.

The principal difference of the surface layer modified with intense pulsed electron beam from the nonmodified volume of the surfacing is the morphology and dimensions of the second phase inclusions. In the modified layer of the surfacing the inclusions have smaller dimensions (in comparison with the volume of the surfacing) and are located mainly in the form of comparatively thin interlayers along grain boundaries. In the volume of the surfacing nonmodified with electron-beam processing the main morphological type of the inclusions is the facet shape particles located chaotically in grain volume.

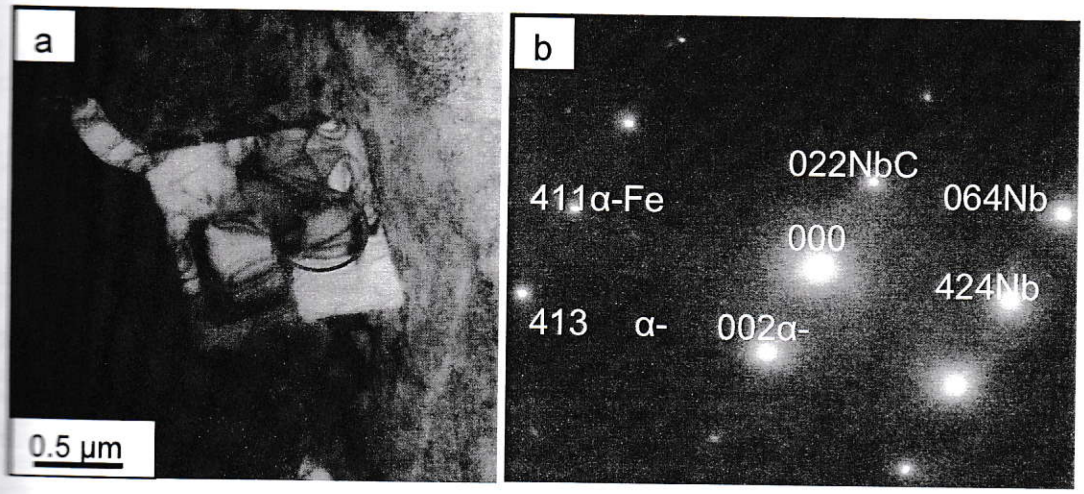

Figure 2 - Structure of surfaced layer modified with electron beam. (a). Microelectron diffraction pattern (b) is obtained from the particle designated by the arrow.

The facet shape niobium carbides are also revealed at 5 mm depth from the electron beam modified surface. The performed tribological tests revealed 70-fold increase in wear resistance of the surfaced layer modified with intense pulsed electron beam in relation to wear resistance of steel.

Fig. 3 shows the change in friction factor in tribological tests of the layer modified with electron beam. The two-stage change in friction factor is noticeable. In the first stage the friction factor value is ≈ 0.17, in the second stage ≈ 0.5. The friction factor of steel without the surfacing ≈ 0.26. When analyzing the change in fraction factor in tribological tests (Fig. 3) it may be supposed that modification of the surfaced layer with intense pulsed electron beams results in substantial (≈ 3-fold) decrease in friction factor of the surfaced layer.

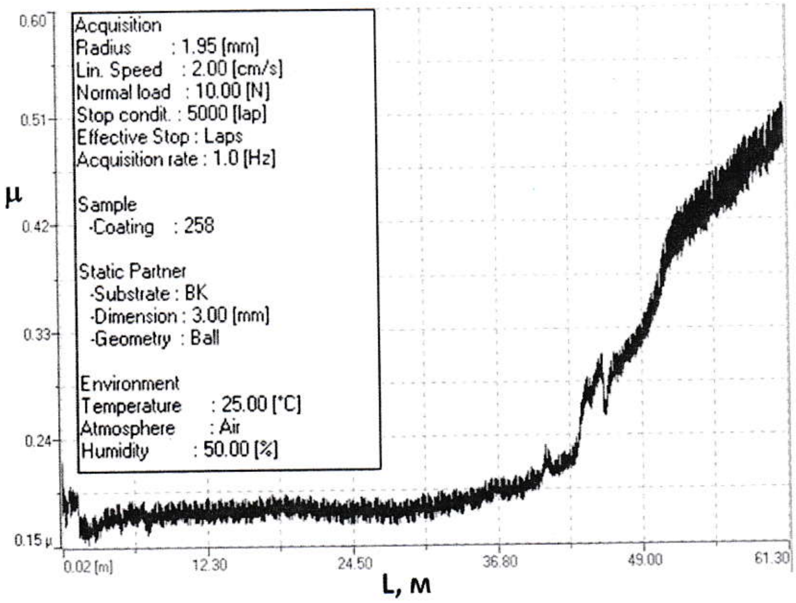

Figure 3 - Dependence of friction factor on track length of tribological tests. The insert shows the conditions of tribological tests.

Conclusion

The studies of structure and tribological properties of the layer formed on Hardox 450 steel by electrocontact surfacing of Fe-C-Cr-Nb-W wire modified by irradiation with high intensity pulsed electron beam have been carried out. It has been shown that electron-beam processing of the welding surface results in the structure refinement and change in morphology of carbide phase of the layer as well as the substantial reduction in its friction factor.

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ОЦЕНКА КАЧЕСТВА УПРОЧНЕННОГО СЛОЯ ПОСЛЕ ПОВЕРХНОСТНОГО ПЛАСТИЧЕСКОГО ДЕФОРМИРОВАНИЯ В СТЕСНЕННЫХ УСЛОВИЯХ

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Аннотация: *Рассмотрено влияние условия деформирования (свободное и стесненное) на характеристики качества поверхностного слоя упрочненных деталей: шероховатость, остаточные напряжения, глубина наклепа, твердость и микротвердость. Выявлена эффективность упрочнения при деформировании в стесненном условии нагружения по сравнению с деформированием локальным свободным нагружением.*

Ключевые слова: *стесненное условие деформирования, пластическая волна, пластическое деформирование, упрочнение, характеристики поверхностного слоя.*

QUALITY EVALUATION OF SURFACE LAYER AFTER SURFACE PLASTIC DEFORMATION IN CONSTRAINED CONDITIONS

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Abstract: *The purpose of the article is to consider the influence of the deformation conditions (free and cramped conditions) on the characteristics of the surface layer quality: roughness, residual stress, depth of hardening, hardness and micro-hardness. Determining the effective hardening during deformation in cramped conditions of loading, which compared with the free local loading.*

Keywords: *constrained deformation, plastic wave, plastic deformation, hardening, surface layer quality.*

Введение. Поверхностное пластическое деформирование (ППД) является одним из наиболее простых и эффективных методов отделочно-упрочняющей обработки деталей машин. ППД повышает усталостную прочность, контактную выносливость и износостойкость деталей и тем самым увеличивает долговечность машин [1-4]. Управление напряженным состоянием при отделочно-упрочняющей обработке поверхностным пластическим деформированием имеет большое значение для изготовления изделий повышенного качества. Например, при обработке маложестких стержневых изделий сложно получить необходимую интенсивность напряженного состояния, т.к. повышенное давление на деформирующий инструмент приводит к искажению геометрической формы самого изделия. При изготовлении тонкостенных деталей иногда требуется снизить напряженнное состояние в очаге пластической деформации, чтобы в процессе формообразования исключить перенаклеп или увеличение