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Short Report
Краткое сообщение

Structural-phase states and properties of high-speed surfacing after tempering and electron beam processing

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***Abstract**.* In this work, the authors used the methods of modern physical materials science to investigate the structure, defective substructure, phase composition, tribological and mechanical properties of the surfacing subjected to high-temperature tempering at 580 °C and subsequent electron beam processing. The deposited layers up to 10 mm thick are formed by plasma surfacing with PP-18YU powder wire in a nitrogen medium. According to the phase composition, the deposited layers consist of α-Fe and carbides of Me_6C composition. After tempering, the polycrystalline structure of the deposited layer contains grains of 7.0 – 22.5 μm in size with layers of the second phase along the boundaries and at the joints of grains with composition V_4C_3, Cr_7C_3, Fe_3C, $Cr_{23}C_6$, WC_{1-x}. Electron beam processing forms a thin surface layer (30 – 50 μm) with grains of cellular (columnar) structure of high-speed crystallization of submicron (100 – 250 nm) size. Particles of the second phase of the nanoscale range of globular and faceted shapes were detected in the volume of grains and along the boundaries.

Keywords: high-speed steel, structure, phase composition, electron microscopy, mechanical and tribological properties

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Структурно-фазовые состояния и свойства быстрорежущей наплавки после отпуска и электронно-пучковой обработки

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***Аннотация**.* В работе авторы методами современного физического материаловедения исследовали структуру, дефектную субструктуру, фазовый состав, трибологические и механические свойства наплавки, подвергнутой высокотемпературному отпуску при 580 °С и последующей электронно-пучковой обработке. Наплавленные слои толщиной до 10 мм формируются плазменной наплавкой порошковой проволокой ПП-18Ю в среде азота. По фазовому составу наплавленные слои состоят из α-Fe и карбидов состава Me_6C. После отпуска поликристаллическая структура наплавленного слоя содержит зерна размером 7,0 – 22,5 мкм с прослойками второй фазы по границам и в стыках зерен составов V_4C_3, Cr_7C_3, Fe_3C, $Cr_{23}C_6$, WC_{1-x}. Электронно-пучковая обработка формирует тонкий поверхностный слой (30 – 50 мкм) с зернами ячеистой (зеренной) структуры высокоскоростной кристаллизации субмикронного (100 – 250 нм) размера. В объеме зерен и по границам выявлены частицы второй фазы наноразмерного диапазона глобулярной и ограненной форм.

Ключевые слова: быстрорежущая сталь, структура, фазовый состав, электронная микроскопия, механические и трибологические свойства

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Introduction

In the mining, metallurgical, and construction industries, surfacing is applied to protect products from various types of wear, corrosion, and static and dynamic loads, ensuring high functional properties [1; 2].

Recently, scientific research and practical developments in plasma surfacing with high hardness materials (R18, R6M5, R2M9, and others) using nitrogen as an alloying element have been actively advancing [1]. When selecting a surfacing material that meets operational conditions, it is crucial to thoroughly investigate the structure, phase composition, mechanical, and tribological properties, as well as their evolution during subsequent heat treatment [3].

It is important to note that surface layers play a significant role, and the formation of microdefects in these layers can lead to macro-failure. In this regard, developing highly effective methods for forming surface layers with high performance characteristics on working surfaces becomes relevant. This problem can be addressed by traditional strengthening methods (chemical-thermal, mechanical, physical, etc.) [3]; however, in some cases, these methods do not ensure good adhesion to the substrate. From this perspective, electron beam processing (EBP) is an effective method, significantly enhancing the mechanical properties of the entire material by optimizing the structural-phase states of surface layers [4]. The application of EBP is considerably more effective than traditional material processing methods.

The aim of this study is to investigate the structural-phase states and properties of surfacing formed in a nitrogen-rich protective and alloying environment from high-speed steel R18Yu during subsequent high-temperature tempering and EBP.

Materials and method

The material used for the study consisted of 30KhGSA steel samples with a deposited layer of R18Yu steel. The deposited layer was applied using plasma surfacing in a nitrogen environment, with the use of non-current-carrying powder wire PP-R18Yu. The chemical composition of R18Yu steel (wt. %): C 0.87; Cr 4.41; W 17.00; Mo 0.10; V 1.50; Ti 0.35; Al 1.15; N 0.06; the balance is iron. During plasma surfacing, the consumption of the shielding gas (nitrogen) Q_{shield} was 20 – 22 l/min, and the consumption of the plasma-forming gas (argon) Q_{plasma} was 6 – 8 l/min. The methodology of plasma surfacing and the justification for the chosen mode are detailed in previous works [1; 2]. The studies were conducted after surfacing, high-temperature tempering at a heating temperature of 580 °C (holding time 1 h, with four tempering cycles), and EBP. The irradiation was carried out with an electron beam energy density of 30 J/cm^2. The pulse duration was 50 µs, the number of irradiation pulses was 5, and the pulse repetition frequency was 0.3 s^{-1}.

The investigation of the structure, defect substructure, phase, and elemental composition was performed using scanning electron microscopy (KYKY-EM 6900) and transmission electron microscopy (JEM-2100 JEOL) [5 – 7]. Microhardness was measured by the Vickers method (HVS-1000 device) with a load of 1 N on the indenter, and tribological properties were evaluated using a Pin on Disc and Oscillating Tribotester.

Results and discussion

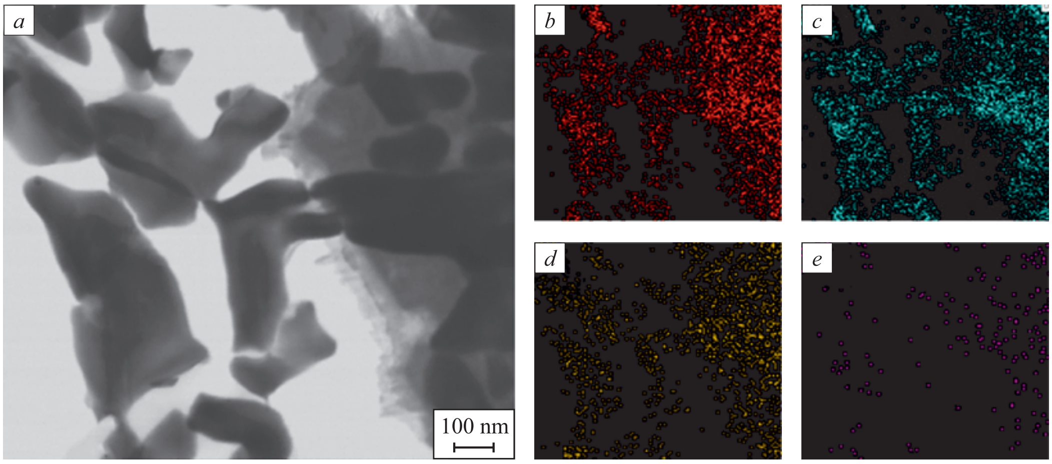
Plasma surfacing forms a layer in which the main phases are α-Fe and Me_6C carbides, which create a carbide network and serve as the primary strengthening phase. During the formation of the deposited layer, nanosized particles of the carbide phase form within the grains. The values of microhardness H_μ, wear rate V, and friction coefficient k are provided in the Table.

After high-temperature tempering, the grain size ranges from 7.0 to 22.5 µm. The results of the elemental composition study, conducted by mapping the frame mesh of the deposited layer, indicate that the mesh grains are enriched with tungsten, iron, and chromium atoms (see the Figure). Analysis of micro-electron diffraction patterns shows that the frame is composed of complex carbides Fe_3W_3C (Fe_2W_4C). The carbide phase grain sizes range from 80 to 350 nm. Mapping of the solid solution grains based on α-Fe shows the presence of tungsten, chromium, vanadium, iron, and carbon atoms, suggesting the presence of nanosized particles of complex carbide phases. These particles are round or faceted in shape, with sizes ranging from 10 to 18 nm.

Microhardness and tribological parameters of the deposited layer

Микротвердость и трибологические параметры наплавленного слоя

State	H_μ, GPa	$V \cdot 10^6$, mm^3/(N·m)	k
Deposition	4.7	8.9	0.70
Deposition + tempering	5.3	9.9	0.65
Deposition + tempering + EBP	5.3	3.3	0.58



Electron microscopic image of a frame mesh section of the deposited layer:
a – light field; *b* – *e* – images of the foil section obtained in characteristic *X*-ray radiation of atoms W (*b*), Fe (*c*), Cr (*d*), C (*e*)

Электронно-микроскопическое изображение участка каркасной сетки наплавленного слоя:
a – светлое поле; *b* – *e* – изображения данного участка фольги, полученные в характеристическом рентгеновском излучении атомов W (*b*), Fe (*c*), Cr (*d*), C (*e*)

Analysis of the corresponding micro-electron diffraction patterns shows that the globular particles, randomly distributed within the α-Fe grains, are carbides of compositions V_4C_3 or Cr_7C_3. The faceted particles are carbides of compositions $Cr_{23}C_6$ ($Me_{23}C_6$), Fe_3C or WC_{1-x}.

After tempering, the microhardness increases by 13 %, reaching 5.3 GPa, the wear rate increases by 12.3 %, and the friction coefficient decreases by 7 % (see Table).

Electron beam processing (EBP) of the tempered deposited layer forms a thin (30 – 50 μm) surface layer with a cellular (grain) structure of high-speed crystallization with submicron grain sizes (100 – 250 nm). Particles of the second phase, with transverse sizes of 10 – 15 nm, are located along the crystallization cell boundaries. In some cases, particles of faceted or globular shape, up to 45 nm in size, are detected at the boundaries and within the cells. Second-phase particles are also observed within the cells, with particle sizes ranging from 5 to 10 nm. Analysis of the micro-electron diffraction patterns indicates that these are complex carbides Me_6C, $Me_{23}C_6$, Me_3C, and Me_7C_3 (where *Me* represents chromium, iron, and tungsten). EBP results in a multiple (threefold or more) increase in the material's wear resistance, a reduction in the friction coefficient, while maintaining the same microhardness.

Conclusions

Using modern physical materials science methods, the structure, elemental and phase composition, defect substructure, and mechanical and tribological properties of the deposited layer of R18Yu high-speed steel in a nitrogen-based protective-alloying environment, subjected to high-temperature tempering and additional irradiation by a pulsed electron beam in the mode of high-speed melting of the thin surface layer, were studied.

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