Pulse Electron Beam Modification of TiC-NiCr Hard Alloy[1]

S.V. Grigoriev, Yu.F. Ivanov, N.N. Koval, V.N. Devyatkov,
V.E. Ovcharenko*, S.G. Psakhie*, V.A. Chudinov*

Institute of High Current Electronics, 2/3 Akademichesky ave., Tomsk, 634055, Russia,
Tel.+7-3822-491713, Fax +7-3822-492-410, E-mail: yufi@mail2000.ru
**Institute of Strength Physics and Material Science SB RAS, Tomsk, Russia*

Abstract – Methods of SEM, TEM and X-Ray diffraction have been used for investigation of irradiation and fracture surfaces, phase composition and defect substructure of surface layer of TiC-NiCr hard alloy treated by low-energy high current electron beam with microsecond pulse duration. Significant changes of structure and phase composition of the modified layer have been found. The changes include the formation of a composite structure layer with increased dispersivity of carbide particles and metal binder in nanostructural state.

1. Introduction

High-energy electron beam pulse treatment is an effective method for modifying surface layer of goods made of different materials (steel [1, 2], hard alloys [3–5], sprayed coatings 6) with the aim of improving the operational data. Comparing to widely used laser technology, electron beam technology has more opportunities for controlling the amount of current input, is differed by improved energy distribution in the surface layer of the treated material as well as high efficiency. Ultra-high speed of heating (up to 10^6 grad/s) of thin surface layer of the material (10^{-4}...10^{-3} mm for electron beams) to melting temperature and the generation of limit temperature gradients (to 10^7...10^8 grad/m) providing cooling the surface layer due to heat sink to the main volume of the material with the speed of 10^4...10^9 grad/s create conditions for generating non-equilibrium structural and phase states in the surface layer. The states are characterized by high density of defects and substructure dispersivity comparing to the initial material state, high concentration gradient of alloying element in a surface layer of the material, etc.

The present paper shows the results of investigation of pulse irradiation influence by electron beam on the surface of ceramic metal alloy based on titanium carbide (TiC) with nickel chromium binder.

2. Materials and methods of investigation

The plates of 10×10×4 mm size made of hard alloy based on titanium carbide (TiC) with nickel chromium binder have been used as a material for studying. The electron beam treatment was carried out on installation "SOLO" by electron beam with pulse duration of 50, 100, 150, 200 μs in the regime of single pulses (number of an irradiation pulses of 15) with beam energy density up to ~40 J/cm^2. Investigation the state of the irradiation surface and fractography of the surface under destruction, element and phase composition, defect substructure of the surface layer of the modified specimens has been performed by methods of SEM and TEM, X-ray diffraction.

3. Results and discussion of investigation

It was established that electron beam treatment with pulse duration of $(5–20)\cdot10^{-5}$ s in the regime of single-shot pulse with the energy density in a beam up to 40 J/cm^2 leads to melting the surface layer of ~5 μm thickness (Fig. 1). The melted layer thickness decreases to ~1 μm with the increasing of pulse to $2\cdot10^{-4}$ s.

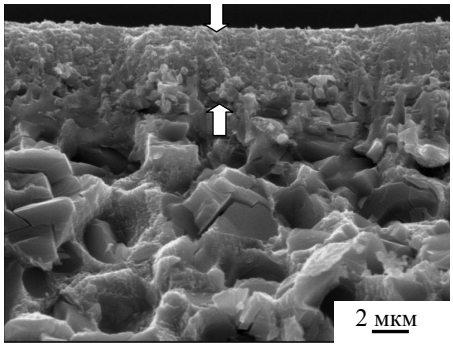

Fig. 1. Fractography of the failure surface of TiC-NiCr hard alloy treated by electron beam (40 J/cm^2, 50 μs). The arrows mark the layer forming from the melt

High-speed heating, melting and further fast crystallizing melt promotes smoothing the surface relief and formation of mirror-like brightness. Vitreous layer typical for the structure with crystallite size of tens hundreds nanometers is formed at influence pulse duration of ~50 μs (Fig. 2).

At that there is a crack network on irradiation surface. The last one is connected with high-speed heating and cooling of a surface layer. It should be mentioned, that with increasing of pulse duration the number of

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microcracks is reduced. At pulse duration of 200 μs the microcracks on irradiation surface are absent (Fig. 3).

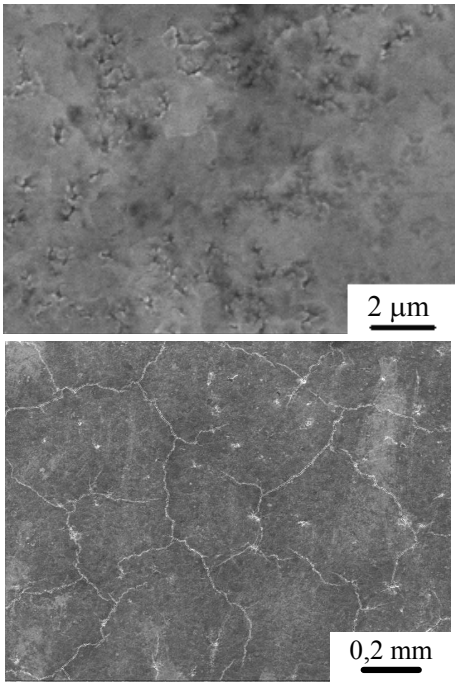

Fig. 2. Structure of an irradiation surface of TiC-NiCr hard alloy, treated by electron beam (40 J/cm^2, 50 μs, 15 pulses)

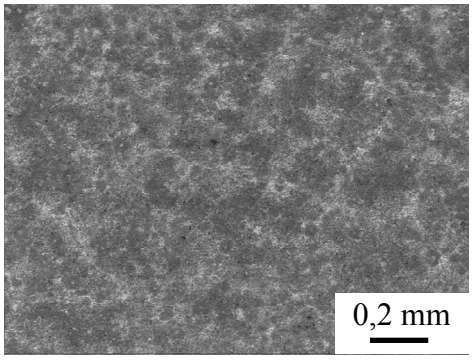

Fig. 3. Structure of an irradiation surface of TiC-NiCr hard alloy, treated by electron beam (40 J/cm^2, 200 μs, 15 pulses)

Increasing the pulse duration of electron beam the structure typical for high-speed crystallization of multiphase materials is formed on the irradiation surface. Namely, undissolved titanium carbide particles surrounded by bind are observed. Typical feature of forming structure is an equalization of carbide phase particles according to their sizes. The equalization occurs in the result of brittle fracture of the coarsest particles due to thermal stress provided by the high speed heating and cooling of the material. Before irradiation the size of titanium carbide particles changed within (0,8–7,5) μm, after the treatment by electron beam of 100 μs, the size changed within (0,5–5) μm (Fig. 4, crack in titanium carbide are marked with arrows).

Crystallization of binding material is accompanied by forming dendrite structure (Fig. 4). Grain size of dendrite crystallization little depends on pulse duration of electron beam and changes within 2,5–4 μm. Using correlation between cooling speed V and the size of interdendrite space d [6], the evaluation of average speed of alloy cooling was carried out. At average values the following parameters are d=0,185 μm (40 J/cm^2, 200 μs, 15 pulses) V=7,06·10^6 K/s.

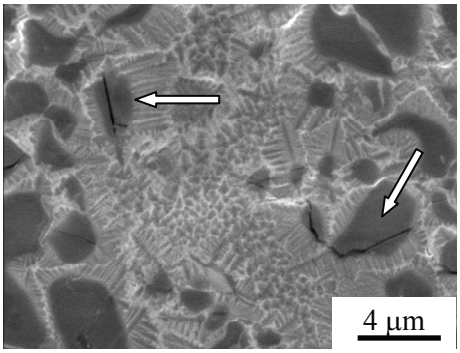

Fig. 4. Structure of an irradiation surface of TiC-NiCr hard alloy, treated by electron beam (40 J/cm^2, 200 μs)

Partial solution of carbide phase under electron beam treatment leads to enriching the binder with titanium and carbon. The analysis of hard alloy elements of different surface sections has been carried out using SEM-515 "Philips", equipped with a microanalyser EDAX ECON IV (Fig. 5). Titanium concentration in the binder changes within (19–29) wt % and reaches maximal values near the section boundary "carbide/binder" (Table 1).

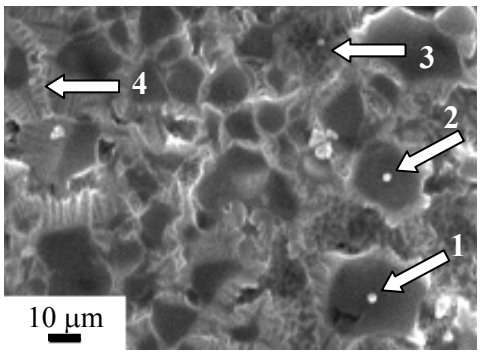

Fig. 5. Irradiation surface structure of TiC-NiCr hard alloy treated by electron beam (40 J/cm^2, 200 μs). The arrows mark sections of the analyzed elements; sections numbering in the figure and table 1 are the same

The discovered enrichment of the binder with titanium and evidently carbon allowed to suppose that the melt crystallization will be accompanied by discharge of carbide phase particles. Actually methods of scanning electron microscopy allow to find allocation of particles of sub micro- and nanometer range in the binder.

Detailed analysis of phase composition and defect substructure of surface layer of hard alloy treated by electron beam has been performed using diffraction

electron microscopy of thin foils. It was established that hard alloy electron beam treatment with pulse duration 200 μs and beam density ~40 J/cm^2 is accompanied by, firstly, binder dispersion hardening due to precipitation of nanoparticles (60–75 nm) of titanium carbide TiC and titanium aluminide Al_2Ti (Fig. 6); secondly, formation of cellular crystallization is divided by titanium carbide interlayer (Fig. 7); thirdly, deformation hardening leads to forming cellular and cellular-network dislocation substructure, in the result of the performed research. Obviously the discovered variety of structure and phase composition of the hard alloy surface layer was determined by non-homogeneous distribution of alloying elements depending on the alloying element concentration (titanium and carbon) what has been mentioned above.

Table I. Results of the analyzed elements of hard alloy surface treated by electron beam (40 J/cm^2, 200 μs)

Point of the analysis	Element	wt %
1	Ti	95,69
	Ni	4,31
2	Ti	83,65
	Ni	10,44
	Cr	5,92
3	Ti	18,94
	Ni	70,12
	Cr	10,94
4	Ti	28,74
	Ni	59,64
	Cr	11,62

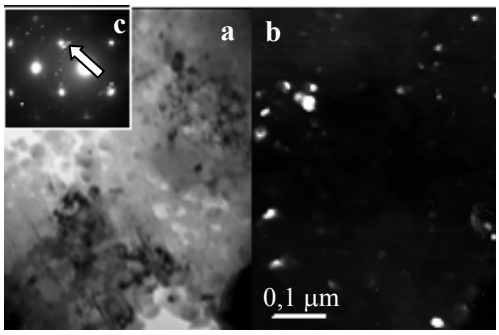

Fig. 6. Structure of the binder formed in surface layer of TiC-NiCr hard alloy, treated by electron beam (40 J/cm^2, 200 μs). a – TEM bright field image; b – TEM dark field image, obtained in [002] TiC reflection; c – diffraction pattern to (a), the arrow marks the dark field reflection

Hard alloy electron beam treatment with pulse duration of 50μs and beam density of ~40 J/cm^2 is accompanied by, as it was mentioned above, the formation of vitreous layer on the irradiation surface. The electron diffraction analysis of the given layer revealed multiphase structure composed of submicron particles of titanium carbide (200–250 nm) (Fig. 8, *a*) and metal binder in nanocrystal condition. The typical structure of diffraction pattern of the binder is characterized by a round construction (Fig. 8, *b*).

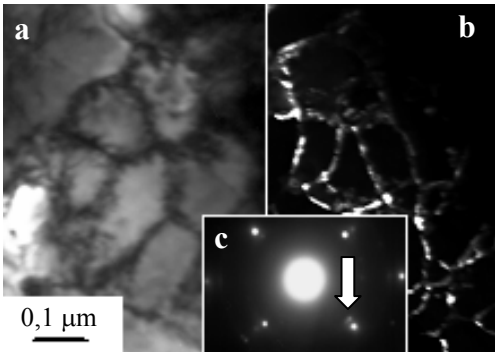

Fig. 7. The structure of cellular crystallization of the binder forming in surface layer of TiC-NiCr hard alloy, treated by electron beam (40 J/cm^2, 200 μs). a – TEM bright field image; b – TEM dark field image, obtained in [002] TiC; c – diffraction pattern to (a), the arrow marks the dark field reflection

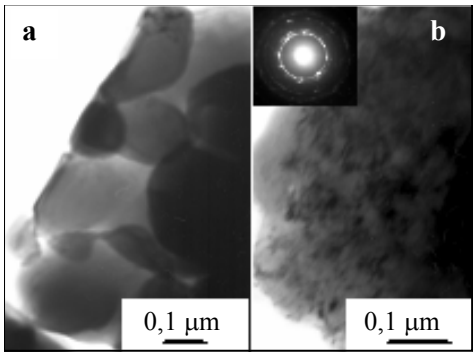

Fig. 8. Binder structure formed in the near-surface layer of TiC-NiCr hard alloy, treated by electron beam (40 J/cm^2, 50 μs)

4. Conclusion

Integrated research made by the methods of present-day physical materials science allows concluding that hard alloy treatment with pulse electron beam leads to the substantial changing of the surface layer microstructure. It is observed the reduction of carbide particles size, the increase of density and size uniformity of their distribution as well as significant microstructure modification of the metal binder. The modification is, firstly, in dispersed binder hardening by precipitation of nanosized carbide phase particles, secondly, in deformation hardening by forming dislocation substructure, thirdly, in hardening due to forming cellular crystallization, and, fourthly, in solid solution hardening due to binder alloying with titanium and carbon. In other word in the result of pulse electron beam treatment of hard alloy the modified layer with the composite structure is formed. It is differed increased carbide particles dispersivity and nanostructural metal binder. The modified layer thickness is determined by technological irradiation regimes: length and number of pulses, current density in irradiation pulses.

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