Structure and wear resistance of SHS TiC+HSS composite coatings, obtained by electron beam surfacing

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Abstract. "Titanium carbide – high speed steel (HSS) steel binder" metal matrix composites were synthesized by the wave combustion mode and investigated. Composite powders "TiC+HSS" obtained by crushing of the self-propagating high temperature synthesis (SHS) cakes were used for electron-beam surfacing of the coatings. An microstructure evolution of composite powder granules during of the surfacing is traced. The evolution involves a partial dissolution of the composite granules in the melt of the surfacing bath and subsequent crystallization of dispersed carbide particles in the dendrites form from a liquid metal solution containing titanium and carbon. The microstructure of the deposited coatings correlates with their hardness and abrasive wear resistance. The abrasive wear mechanism of the coatings is discussed.

1. Introduction
High-speed steel is widely used for the manufacture of metal cutting tools. Due to high heat resistance, this steel is also of interest as a material of wear-resistant coatings operating at high temperatures. The important advantage of the HSS for plasma or electron beam surfacing originates from well-known self-hardening effect during cooling of the cladded coating [1].

An additional properties improvement of the coatings cladded with high speed steel powder can be obtained by adding refractory compounds into the powder. Metal carbides are used as the additives most often [2-5]. The TiC carbide appears to be the most effective additive due to the highest hardness, compared to other metal carbides.

The powder mixtures are often used in coating technologies. Components segregation in the powder mixture and during delivery into melted bath can occur. That will result in inhomogeneity of elemental composition of the coating [6-9]. The segregation problem is actual even more in plasma coating technologies. In this case, it is particularly necessary to use granulated composite powders, already composed of carbide particles embedded into metal binder.

Self-propagating high-temperature synthesis in powder reaction mixtures of carbon, a carbide forming metal, and matrix metal should be recognized as the most technologically and highly productive way of obtaining composite powders "dispersed carbide-metal binder" [10].

SHS composite powders "titanium carbide – HSS binder" were obtained and investigated earlier [11]. In the present work, these powders were used for electron beam surfacing of coatings. The aim of
the work was to trace the evolution of the morphology, dispersion and structure of SHS powders in the process of surfacing and to investigate the influence of the structure of the deposited coatings on their hardness and wear resistance.

2. Materials and experimental procedures

Porous SHS cakes with target binder content from 20 to 50 vol. % were obtained by the wave combustion mode of cylindrical 20 and 35 mm in diameter compacts consisting of powder mixtures of titanium (<190 μm), carbon black (~8 μm) and high-speed steel (<90 μm). Titanium powder contained not less than 99.4 % base component and main impurities were: Fe – 0.33%; Cl – 0.12%; oxygen – less than 0.1%. Steel powder contained 1% carbon, the alloying elements (Cr – 4%; W – 6.5%; Mo – 5%; V – 2%) and impurities (Si – 0.5 %; Mn – 0.55%; Ni – 0.4%). Mixtures were prepared by dry mixing for 4 hours. The compacts porosity was about 40%. We failed to obtain more porous compacts due to insufficient strength of the compacts. Synthesis was carried out in a sealed reactor at argon medium under 0.5 bar excess pressure. Combustion was initiated by igniting tablet heated by a molybdenum coil. The surface layer of porous SHS cakes of thickness 1-2 mm was removed. The purified cakes were crashed and separated to the fractions by sieving.

The surfacing was carried out by a special unit [12, 13], which included a vacuum chamber with a pumping system, a powder feeder with a feed control device, a manipulator and an electron gun with a high-voltage power supply and a control system. The composite powders were doped with steel powder to obtain an integral binder content of 80 vol. %. That increased the cladding ability of powder mixtures. The coatings were cladded on low-carbon steel 4 mm thick substrates under the following conditions: electron energy 27 keV, continuous beam current 100 mA, scanning electron beam amplitude 10 mm, longitudinal advance velocity 3 mm / s

Structure studies of coatings were carried out at the Centre of collective usage “NANOTECH” in the Institute of strength physics and materials science of Siberian branch of Russian Academy of Sciences (ISPMS SB RAS) by optical microscopy (AXIOVERT-200MAT) and scanning electron microscopy (LEO EVO 50).

To compare the properties of coatings cladded with HSS steel powder and with composite powders, hardness was measured and abrasive wear tests were carried out in accordance with GOST 23.208-79 “Method for abrasive wear testing by friction against unfixed abrasive particles”. Electrocorundum No. 16-H with a grain size of 160-200 μm was used as an abrasive. The microhardness was measured by PMT-3 device with 100 g (0.981 N), indenter load and Vickers hardness by Duramin-500 (Stuers A / S, Denmark) with 500 g indenter load.

3. Results and discussion

3.1. Microstructure of surfaced coatings

Coatings cladded by multipass electron-beam surfacing, have 2–5 mm thick (depending on the number of passes). A middle part of the coatings (outside of coating-substrate transition zone) has a specific structure including the grains of the composite powder and individual carbide inclusions embedded into the steel matrix (figure 1). Thus, under the used surfacing regimes, the composite coatings have a structure including strengthening elements of two different scales: granules of more, than 100 μm size and individual carbide inclusions in the steel matrix.

It can be assumed that with the same integral content of the steel binder in the cladded coatings (80 vol. %) hardness and wear resistance can be affected by structural characteristics such as the volume content and average size of the non-dissolved granules, as well as the volume content and average size of the individual carbide inclusions in the steel binder. We cladded two kinds of coatings, using powder mixtures containing composite powder granules of different size. A metallographic study of the deposited coatings showed that the average size of the rest granules in the deposited coatings depended both on the initial size of the granules of the composite powders and on the content of HSS binder in the granules (figure 2). The average size of the rest granules in the coatings decreases
in comparison with the size of composite powders in the starting powder mixtures. This can be explained by the dissociation of the outer part of the granules due to melting with the release of carbide particles.

![Figure 1](image1.png)

**Figure 1.** The microstructure of surfaced coatings from composite powders with a HSS binder content (vol. %): a) 20%; b) 30%; c) 40%; d) 50%.

The origin of individual carbide inclusions in HSS binder can be different. The major part of them originated from the peripheral part of the granules and were released as a result of melting of the steel binder that has bounded the carbide grains inside the granules. Another minor part of carbide inclusions came out in crystallization process from a liquid metal solution that was supersaturated by carbon and titanium. The liquid solution has formed by the carbides dissolution of the peripheral region granules. These secondary crystallization carbides had an elongated dendritic shape and are most numerous in the coatings cladded with composite powder with 50 vol. % of binder (figure 4d). The volume fraction of secondary carbides is the greater, the greater is the concentration of titanium and carbon in the surfacing bath. This concentration, in turn, is the more the more is the specific area of the carbide-melt interphase boundary per volume unit of the carbide phase, through which the carbides dissolve. The carbide-melt interface specific surface goes up as smaller is the carbide particles size.

3.2. **Microstructure and hardness of the transition zone coating-substrate.**

The transition zone "coating – substrate" is of great importance, since coating adhesion to the substrate depends on its phase composition and structure. Adhesion is the more important because of the large internal stresses in the heat-affected zone arising during the surfacing process. Figure 3 presents the microstructure and microhardness in the cross-section of coating-substrate transition zone.
Figure 2. Dependence of the average size of granules in coatings with composite powders of different dispersity of HSS binder. The initial size of the granules of the composite powder: 1: 125-200 μm; 2: 200-315 μm.

The structure of the near interface area in the coating (figure 3) differs from the bulk structure of the coating (figure 1) by a smaller number of non-dissolved granules and of the individual carbide inclusions. This area is diluted with iron from the molten steel substrate. The micro-hardness varies widely in the bulk part of the coatings due to the structure heterogeneity. The maximum values of microhardness correspond to the microhardness of granules or individual carbide particles, and the minimum values refer to steel substrate microhardness.

Figure 3. Microstructure (a, c) and microhardness profiles (b, d) in the transition zone “coating-substrate” of the coating clad with composite powders: (a, b) – TiC+20 vol. % HSS; (c, d) – TiC+50 vol. % HSS.

The hardness transition from substrate to coatings bulk is smoother in TiC+20 vol. % HSS, than in TiC+50 vol. % HSS (figure 3 b,d). This is in agreement with the wider transition zone for TiC+20 vol. % HSS powder coating (figure 3a) in comparison with the sharp dependence in the TiC+50% HSS powder coating (figure 3c). Such a difference in the microhardness profiles can be explained by the
fact, that the hardness in near interface area reinforced with dispersed carbide particles (figure 3c), in coating, cladded with TiC+50 vol. % HSS powder higher than the hardness in near interface area in the coating, cladded with TiC+20 vol. % HSS powder, in which there are only rare inclusions of the granules (figure 3a). According to the metallography and microhardness profiles in the transition zone of all coatings, there are no hard and brittle layers that could degrade the coating-substrate adhesion.

3.3. Hardness and wear resistance of cladded coatings
The average hardness of coatings cladded with small-scale composite powders granules increases with increasing binder content (figure 4a). A scatter in the coatings hardness values cladded with a large-scale powder is wider, than in coatings cladded with small-scale powder. There is no definite hardness dependence on the content of the HSS binder. It is interesting, that the hardness of the coating, deposited by the steel powder is approximately in the middle of the interval, in which the hardness of coatings cladded with composite powders varies. So it could be stated, that, due to the effect of self-hardening of HSS steel, the titanium carbide additive into HSS binder has little effect on the composite coatings hardness in contrast to its effect on abrasive wear resistance (figure 4b). The wear resistance of coatings cladded by a small-scale composite powders is 2.3 times higher than the wear resistance of HSS coatings, and approximately 4.7 times higher for coatings cladded with large-scale powders. The reasons for this dependence of the wear on the dispersion of the deposited powder, as well as on the wear mechanism, can be explained by the pictures of worn surfaces (figure 5).

![Figure 4](image_url)  
**Figure 4.** Dependence of hardness (a) and wear rate (b) of coatings from HSS powder and powder mixtures with different content of steel binder in SHS composite powders. The integral content of HSS in the powder mixtures is 80 vol. %. 1: cladding with powders of 200-315 μm; 2: cladding with powders of 125-200 μm.

![Figure 5](image_url)  
**Figure 5.** Pictures of worn coating surfaces from HSS powder (a) and from composite powder TiC+20%HSS (b – side view).
The parallel grooves on the worn surface of the HSS surface (figure 5a) points on the microcutting wear mechanism of the steel by sharp corundum particles with about 20 GPa hardness. Composite coatings wear mechanism is influenced by the rest granules in the composite coatings structure. The dispersed carbide particles in the granules structure are firmly bound with a steel binder, which provides sufficient viscosity of the granules and prevents them from brittle fracture under the abrasive grains action. The granules stand out over the surface (figure 5b), prevent the abrasive particles contact with the steel binder of inter-granular interlayers and result in the wear rate decrease. The smaller the granules (with the same volume fraction) are, the more they are per unit area of the wear surface and, correspondingly, the smaller the intergranular interlayers width of the steel binder and the less their wear by relatively large (160-200 microns) abrasive grains. This explains the lower wear rate of coatings cladded with fine powders (see figure 4b).

4. Conclusion

1. Electron-beam coatings cladded with SHS composite TiC+HSS binder have been studied. The coatings composed of the steel matrix and two different-scale strengthening elements: non-dissolved granules of composite powder with a size of more than 100 μm and separate carbide inclusions in a steel binder.
2. Due to the self-hardening effect of high-speed steel at cooling of the surfacing bath, the titanium carbide additive into the structure of the cladded coatings has little effect on their hardness.
3. The abrasive wear resistance of coatings cladded with composite powders depends on the dispersion of the composite powders in the coatings and in 2.3-4.7 times higher, than wear resistance of HSS coatings.
4. The increase in the abrasive wear resistance of coatings is provided, mainly, by composite powder grains, which stand up over the wear surface and prevent the wearing of steel binder.

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