Technology of Strengthening Steel Details by Surfacing Composite Coatings

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Abstract. The article considers the problem of forming wear resistant meal ceramic coatings on steel surfaces using the results of our own investigations and the analysis of achievements made in the country and abroad. Increasing the wear resistance of surface layers of steel details is achieved by surfacing composite coatings with carbides or borides of metals as disperse particles in the strengthening phase. The use of surfacing on wearing machine details and mechanisms has a history of more than 100 years. But still engineering investigations in this field are being conducted up to now. The use of heating sources which provide a high density of power allows ensuring temperature and time conditions of surfacing under which composites with peculiar service and functional properties are formed. High concentration of energy in the zone of melt, which is created from powder mixtures and the hardened surface layer, allows producing the transition zone between the main material and surfaced coating. Surfacing by the electron beam directed from vacuum to the atmosphere is of considerable technological advantages. They give the possibility of strengthening surface layers of large-sized details by surfacing powder mixtures without their preliminary compacting. A modified layer of the main metal with ceramic particles distributed in it is created as a result of heating surfaced powders and the detail surface layer by the electron beam. Technology of surfacing allows using powders of refractory metals and graphite in the composition of powder mixtures. They interact with one another and form the particles of the hardening phase of the composition coating. The chemical composition of the main and surfaced materials is considered to be the main factor which determines the character of metallurgical processes in local zones of melt as well as the structure and properties of surfaced composition.

1. Introduction
Surfacing technology of hardening coatings which allow increasing the durability of steel details under intensive wearing is widely used in industry for more than 100 years. Nowadays a great variety of electrodes, wires and powder mixtures intended for gas thermal, electric arc and plasma coating of wear resistant materials on steel details are produced and offered on the market. The composition of surfacing materials as well as the composition of the main detail metal determines the structure and properties of the layer surfaced which presents the material as a steel matrix with evenly distributed hard particles of carbides, borides and intermetallics [1-4]. Hard particles determine the wear resistance of the surfaced layer. They are either present in the surfacing materials composition or formed from power mixture components as a result of chemical and thermal processes during surfacing. Compositions of surfacing materials and surfacing modes used determine the result obtained. Attempts to surface materials, the structure and properties of which were identical to those of sintered hard alloys with the framework of refractory ceramic particles in metallic bond are not
successful up to now. First of all, it is explained by the fact that in surfacing the coating it is impossible to get the framework of refractory particles because the matrix material strengthened by phase particles, the hardness of which is in several times higher than that of the matrix, is always formed. Besides, the surfacing process is accomplished by forming the liquid phase, which is typical of metallurgical processes in micro volumes of surfaced and main materials. Technology of strengthening surface layers of steel details must solve the problem of compatibility between coating materials and the main metal in two aspects: thermo mechanical and physicochemical. The thermo mechanical aspect supposes the absence of expansion voltage in the coating formed and the presence of the transition zone between the coating and the main material, which excludes the composition destruction on the border – “the coating – the main material”. The physicochemical aspect of compatibility between the material coating and the main metal means excluding the formation of fragile phases both in the coating and in the transition zone. Technology of strengthening steel details by surfacing the composite coatings provides their high service properties and is determined by the chemical composition of steel and the surfaced material.

2. Conditions of Experiments

2.1. Materials
Mixtures of refractory metal carbides with metallic powders as well as mixtures of metals forming carbides and borides with graphite, iron and other metals were used as surfacing materials. Table 1 presents the information on initial powder materials of which surfacing mixtures were produced.

Table 2.1. Chemical composition of powder materials (chemical elements and compounds) used in the experiments

| Properties of Powder Material | WC* | WC [5,6] | TiC | B4C | B** | C*** | Ti | Ta | V | Mo | Co | α-Fe |
|------------------------------|-----|---------|-----|-----|-----|------|----|----|---|----|----|------|
| Particle size, µm            | min | 4       | 2   | 3   | 14  | 1    | 30 | 50 | 0.7 | 1   | 2   | 1    | 5    |
|                              | max | 13      | 5   | 13  | 28  | 30   | 80 | 90 | 5   | 30  | 5   | 2    | 30   |
| Presence of Oxygen in particles, % per mass | <0.3 | <0.3 | -   | -   | <3.5 | <0.7 | <0.7 | 0.5 | 1.38 | <1.4 | <4.7 |

Notes:
* content of fixed carbon 5.8 – 6.2 % per mass and free carbon – not more than 0.1 %;
** boron in the amorphous state;
*** graphite powder

Surfaced powder mixtures were laid on the surface of flat samples by different methods: by filling, through sprinkling the concentrated suspensions with further drying. To increase density, powder mixtures on the samples were subject to packing by the manual press before surfacing.

During surfacing heating in the air atmosphere salts MgF2, CaF2 and LiF were added to powder mixtures, which limited oxidizing processes in melt.

Steel with the carbon content of up to 0.8% without alloying components or containing not more than 1% of chrome was used as the main metal.

2.2. Methods of Surfacing
Surfacing of powder mixtures was conducted by different heating sources: in vacuum radiation furnaces, by the laser beam with a wavelength of 10.6 µm in the air and argon atmosphere, by the electron beam directed from vacuum to the air atmosphere.
Temperature and time modes of sintering were limited by appearing the liquid phase in the whole volume of powder composition laid on the sample of the main metal. The time period during which melt in the surface layer existed was minimized.

2.3. Assessment of Physical, Mechanical and Service Properties of Compositions

After visual assessment the hardness of surfaced coatings was measured under different loads, which allowed determining not only the ability of the coating to resist deformation under high specific loads but also served as an indicator of property variation in the coating volume – from the transition zone to the surface layer. Measurements were conducted on hardness meter 402 MVD on frontal and cross sectional cuts of compositions. The composition strength was estimated by device 8801, the destruction viscosity was determined on the pile driver Metro Com 06103300. To analyze cause-and-effect links between composition properties and surfacing modes the structure of surfaced layers was studied by the optical microscope Carl Zeiss Axio Observer Alm and scanning microscope Carl Zeiss EVO 50 XVP.

Wear resistance of surfaced coatings was determined by friction against fixed abrasive particles (silicon carbide and aluminum oxide) with the seed size of 80 … 100 µm by comparing with industrial sintered hard alloy and steel 40X after hardening with further low tempering.

3. Results and discussion

The main difference in methods of surfacing used consisted in temperature-and-time heating modes and cooling of steel samples with laid powder mixture. During the experiments it was discovered [7] that in surfacing powder mixtures containing tungsten monocarbide on steel detail compound carbides of type (Fe,W)6C which are very fragile are always present in the transition zone. The formation of these carbides takes place under temperatures of over 710°C. Despite their instability they are preserved in the surfaced composition after its cooling because of lack of carbon. Increase in the heating velocity and cooling by laser and electron beam heating allows reducing the size of complicated fragile carbides and providing good strength and high service properties of compositions [8, 9]. To exclude the formation of fragile carbides in the transition layers it is necessary to use the barrier layers between the coating and the main metal. Such layers must have a strong bond with the main metal and the surfaced coating. Saturation of the steel surface layer by boron is effective as the technology of forming barrier layers [10].

The most perspective technology of hardening surface layers of large-sized steel details is out-of-vacuum electron beam surfacing of coatings. As a result of it the hardening phase is created in the process of interacting initial surfaced powders with one another and with the main detail metal. The use of such technology allows reducing the duration of chemical and thermal modification processes of detail surface layers preserving the initial structure of the main metal. In surfacing powder mixtures of iron and amorphous boron [11 - 15], barrier layers of the necessary thickness, composition and structure are formed. Figure 1 shows the structure of the borated layer produced by surfacing the amorphous boron powder mixed with powder α-Fe. A high speed of electron beam surfacing of coatings on large-sized details allows excluding changes in the structure of the main metal. Borated layers with a thickness of 300 to 900 µm can be used both as barrier layers for further surfacing of composite coatings with hardening particles of tungsten carbide and as a wear resistant coating alone.

The investigations of electron beam surfacing conducted on medium-carbon steel 40X of wear resistant composite coatings from powder mixtures “Ti-C”, “V-C”, “Ta-C”, “Ti-Ta-C”, “Ti-Mo-C” allowed making a conclusion that the most perspective compositions are “Ti-Mo-C” and “V-C”. Electron beam surfacing under the accelerating voltage of 1.4 MeV, the current of electron beam of 25 … 28 mA, the beam width of 50 mm and the scanning speed of the treated surface relative to the beam of 0.01 m/s allows forming coatings with a thickness of up to 2.6 mm. They have a matrix structure of the composite material hardened by martensite and particles of titanium and vanadium carbides which are evenly distributed and constitute up to 33% of the coating volume (Figure 2). The coating austenite matrix provides viscosity to the coating and keeps carbide particle firmly, preventing their breaking-off during tribotechnical influence.
**Figure 1.** Structure of the steel 20 surface layer after out-of-vacuum electron beam surfacing of the powder mixture of amorphous boron and $\alpha$-Fe: a – optical microscopy; b – electron scanning microscopy

**Figure 2.** Structure of the steel 40X surface layer after vacuum electron beam surfacing: a, b – powder mixture Ti + Mo + C; c, d – V + C

The distinctive feature of surfaced coatings from the powder mixture “V – C” is the dendrite shape of vanadium carbide particles, while in surfacing the mixtures “Ti – Mo – C” carbides have a round shape similar to equiaxed. Under slipping friction the wear resistance of the coating with vanadium carbide particles is in 2.5 times higher than that of the material with round carbide particles of titanium carbide. Under friction against freely fixed abrasive particles the wear resistance of the material with
carbides of the dendrite shape is three times higher than the wear resistance of the layer with equiaxed particles.

4. Conclusion
Technology of out-of-vacuum electron beam surfacing of composite coatings allows forming wear resistant layers with a thickness of more than 1...2 mm at the surfaces of large-sized steel details with high capacity. In this case there appears a possibility of using materials which during surfacing interact with one another, thus forming the particles of the hardening phase, evenly distributed along the volume of the surfaced layer.

References
[1] Kulkov S.N., Gnyusov S.F. 2006 Karbidostali Na Osnove Karbidov Titana i Volframra (Carbidosteels on the Basis of Carbides of Titanium and Tungsten) (NTL, Tomsk) p. 240
[2] Gnyusov S.F., Tarasov S.Yu. 2013 Structural Phase States and Heat Aging of Composite Electron Beam Clad Coatings Surface and Coating Technologies Vol. 232 775-83
[3] Devoino O.G., Kardapolova M.A., Laber S., Feldstein E.A., D’yachenkova O.V. 2004 Wear Resistance of Coatings from Self-fluxing Alloys after Laser Doping under Dry Friction Conditions [Text] Journal of Engineering Physics and Thermophysics Vol. 77 Iss. 2 372–6
[4] Wang D., Liang E., Chao M. 2008 Investigation on the Microstructure and Cracking Susceptibility of Laser-Clad V2O5/NiCrBSiC Alloy Coatings [J]. Surface and Coatings Technology 202 1371–8
[5] Marusina V.I., Ishkhakova G.A., Rakhimyanov Kh.M. 1992 Phase and particle size composition of carbides formed during electric spark erosion machining of tungsten. Soviet Powder Metallurgy and Metal Ceramics Vol. 31 Iss. 10 870-73
[6] Ishkhakova G.A., Marusina V.I., Rakhimyanov Kh.M. 1987 Determination of the microhardness of tungsten carbide particles produced in the spark discharge. Soviet Powder Metallurgy and Metal Ceramics Vol. 26 Iss. 10 852-4
[7] Burov V.G., Bataev I.A., Tyurin A.G., Veselov S.V. 2015 Structure and Properties of WC-Co Coatings Obtained on Steel Substrates by Liquid State Sintering in Vacuum [Text] Surface Engineering Vol. 31, Iss. 7. 540-4
[8] Gnyusov, S.F. Ignatov A.A., Durakov V.G., Tarasov S.Yu. 2012The effect of thermal cycling by electron-beam surfacing on structure and wear resistance of deposited M2 steel. Applied Surface Science Vol. 263 215-22
[9] Gnyusov S.F., Durakov V.G., Ignatov A.A. 2013 Electron Beam Cladding by HSS R6M5 Powder IEEE Transactions on Plasma Science Vol. 41-8. 2196–200
[10] Burov V.G., Bataev V.A., Veselov S.V., Bataeva Z.B., Sameishcheva T.S. 2012 Surface Layer Formation by Melting Tungsten-Cobalt Powder Mixtures on Steel [Text] Russian Engineering Research Vol. 32-1 95–7
[11] Bataev I.A., Bataev A.A., Golkovsky M.G., Teplykh A.M., Burov V.G., Veselov S.V. 2012 Non-vacuum Electron Beam Boriding of Low-Carbon Steel [Text] Surface & Coating Technology Vol. 207 245–53
[12] Krivezenko D., Drobyaz E., Bataev I., Chuchkova L. 2015 Investigation of the structure and properties of boron-containing coatings obtained by electron-beam treatment AIP Conference Proceedings Vol. 1683 Art. 020104 (4 p.)
[13] Tyurin A., Nagavkin S., Malikov A., Orishich A. 2015 Microstructure of WC-Co hard alloy surface after laser treatment Surface Engineering. Vol. 31, Iss. 1. 74-7
[14] Samoylenko V., Lenivtseva O., Polyakov I., Laptev I. 2015 Structure and mechanical properties of coatings fabricated by nonvacuum electron beam cladding of Ti-Ta-Zr powder mixtures AIP Conference Proceedings Vol. 1683 Art. 020198 (4 p.)
[15] Gromov V., Konovalov S., Bataev V., Ivanov Y., Kobzareva T., Semina O. 2015 The role of electro-explosion alloying with titanium diboride and treatment with pulsed electron beam in the surface modification of VT6 alloy AIP Conference Proceedings Vol. 1683 Art. 020093 (4 p.)