Cladding of the carbon fiber on the steel base using electron beam in the air atmosphere

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Abstract. The formation of the high-carbon layers on the low-carbon steel (0.18 % C) using the method of electron-beam partial melting of the carbon fibers is considered. A 1.4 MeV electron beam extracted into air was used. The features of the cladded layers formation using different binders for a reliable fixation of the cladding material are studied. It is revealed that the best results are obtained using the phenol-formaldehyde glue as the binder. A 3 mm thickness layers with 2.2 % C are shown to be formed.

Keywords: Steel, Carbon fiber, Electron beam cladding, Surface hardening.

1. Introduction
In the up-to-date industry various kinds of high-impact effect on materials such as laser, plasma, electron-beam treatment and high-frequency current treatment gained widespread currency. These methods provided the basis for such technological processes as welding, cutting and various types of the surface hardening (cladding, sputtering, surface alloying, surface quenching) [1-4].

At the present day the surface hardening by high-impact stimulation techniques is one of the most effective mechanisms of ensuring the required performance properties to the material (strength, wear resistance, corrosion resistance, etc.). Due to the surface hardening, increasing the reliability of machine parts and mechanisms and cost reduction of metal products in general is achieved. In addition, high-impact techniques allow replacing thermal and chemical-thermal treatment operations. This work is devoted to surface hardening of steel parts by non-vacuum electron-beam partial melting of carbon fibers.

The advantages of electron-beam treatment are as the follows: high efficiency (over 75%), the ability of the electron-beam scanning by the magnetic field, the lack of impact of the optical properties and surface roughness on the degree of energy absorption, high power electron-beam mount, treatment parameter control flexibility, treatment of large products (during non-vacuum electron beam treatment). The method of electron-beam cladding of carbonaceous materials is a relatively simple process that does not require time-consuming preparation of the surface of the work piece.

In previous works the peculiarities of high-carbon layers formation on steel by deposition of powder materials on flat bars have been studied [5]. However, it should be noted that the consolidation of the powders on the details of complex configuration causes certain difficulties. In this regard the problem was set: exploration the possibility of formation of high-hardened layers during the treatment of carbon fibers and fabrics using the binders.
2. Materials and methods

In the capacity of work pieces for cladding, steel plates with the thickness of 4.5 mm were used. The chemical composition of the used steel work pieces is presented in the Table 1.

| Elements content, % | C  | Mn | Si | Cr | S  | P  |
|---------------------|----|----|----|----|----|----|
| 0.18                | 0.5| 0.23| 0.25| 0.04| 0.035|     |

As a material for forming the cladded high-carbon layers, a carbon fiber GG 210-P was used. The surface density of the material was 0.017 g/cm², the mass fraction of carbon - 99.9%. Due to the fact that carbon does not melt, but is subjected to sublimation at the temperature of 3300 °C, in order to facilitate its dissolution and prevent burnout carbonyl an iron powder OSCH6-2 (TU 6-09-3000-78) was used. The average particle size of the powder was 64 μm. Table 2 shows the chemical composition of the iron powder. Also, to protect the molten pool from the atmospheric agents MgF₂ flux was used. The density of the flux was 0.3 g/cm³, melting temperature - 1263 °C.

| Elements content, % | C  | Ni | Si | Mg | Cu |
|---------------------|----|----|----|----|----|
| 0.02                | 0.02| 0.0005| 0.0001| 0.0001|     |

Iron and flux powders were mixed with a binder. Three types of binders were used: polyvinyl acetate emulsion in water, an alkaline aqueous sodium silicate solution and phenol-formaldehyde glue.

Before applying the cladding material, the work piece surface was cleaned from the oxide and degreased.

The work considers the cladding of high-carbon layers with the density of the cladding materials 0.13 g/cm² and 0.26 g/cm². In the first case, the carbon fiber fabrics was applied in a single layer, in the second case - in two layers, and a mixture of a binder with an iron powder and a flux was applied between the fiber fabrics layers and on top of them (Figure 1.). In all cases, the composition of the deposited material was identical: 13% (wt.) C, 37% (wt.) Fe and 50% (wt.) MgF₂, 100% (wt.) binder.

The work pieces with the applied cladding materials were dried in a furnace at 40 °C until complete binder drying out.

To form high-carbon coatings an industrial electron accelerator ELV6-type, designed and produced by the staff of the Budker Institute of Nuclear Physics SB RAS (Novosibirsk) was applied.

The surface of the work piece during treatment was at a distance of 90 mm from the outlet. Electronbeam energy was 1.4 MeV, beam current - 8 and 10 mA. The treatment took place in the track mode, at 10 and 25 mm/s.
To determine the chemical composition of the resulting coatings an optical emission spectrometer ARL 3460 was used. For carrying out metallographic studies an optical microscope Axio Observer Alm (Carl Zeiss) was used. In the capacity of the subject of research the metallographic sections were prepared using standard techniques, including grinding and polishing operations. To reveal the coatings microstructure, the test method of chemical etching using 5% nitric acid solution in ethanol was used.

3. Results and discussion

Primarily during the experiment, the work pieces with the aqueous alkaline solution of sodium silicate as a binder were treated. The experiment showed that the use of this binder is inefficient, due to the formation of poor quality coatings (Figure 2).

![Figure 1. The model of the cladding materials application](image)

Figure 2. Appearance of the specimen with an aqueous alkaline solution of sodium silicates a binder

The appearance of the samples after electron-beam treatment with a water emulsion of polyvinyl acetate and phenol-formaldehyde glue has no significant differences (Figure 3a, b). It should be noted that when removing the cladded material residues on the sample surface with an emulsion of polyvinyl acetate, corrosion products were observed (Figure 3, c).

Also during the experiment, it was found that applying the mixture of the binder with the powders of iron and flux through the layer of carbon fiber fabrics (Figure 1b) is inefficient, since in this case the wetting components are not sufficient for encapsulation of the top fiber fabrics layer, whereby it is not activated in coating formation (Figure 3, d).

It is worth noting that when heated by high-impact source, the temperature distribution in the material (from the surface layer in depth) varies smoothly. Thus, the highest temperature has a surface layer, and
temperature decreases if and when going from the surface into the material. In connection with this, the structure formed after the surface layer after the high-impact treatment is also nonuniform. Several zones can be distinguished in it: the 1st zone is a cladded layer; the 2nd zone is the transition zone; the 3rd - the heat affected zone; the 4th - the base metal.

Using the cladded material with a density of 0.13 g/cm² and a processing speed of 25 mm/s provides a coating with a thickness of 1.5 mm and a carbon concentration of up to 1.95%. It was revealed during the metallographic investigations that the cladded layer is a hypereutectoid steel, consisting of pearlite and secondary cementite (Figure 4a). And in the local areas the presence of zones with quenching structures (retained austenite and martensite) was recorded (Figure 4b). The transition zone is composed of perlite, its thickness is 150 μm. Heat affected zone includes pearlite and wide manstatten ferrite.

Figure 3. Appearance of the specimen with a) a polyvinyl acetate emulsion in water; b) phenolformaldehyde glue; c) a polyvinyl acetate emulsion in water after removing the cladded material residues; d) phenol-formaldehyde glue with the applied powders of iron and flux through the layer of carbon fiber fabrics
Figure 4. The structure of the cladded layer, obtained at the cladding material density of 0.13 g/cm$^2$ and a treatment rate of 25 mm/s.

To ensure good fusion penetration and mixing of the materials with high density of the cladded material up to 0.26 g/cm$^2$ is a reasonable to reduce the treatment speed to 10mm/s. As a consequence coatings with a 3 mm thickness, in which the carbon concentration was 2.2% were obtained. In this case the structure of the cladded layer along with secondary cementite and pearlite has a ledeburite (Figure 5).

Figure 5. The structure of the cladded layer obtained in the deposited material density of 0.26 g/cm$^2$ and a treatment rate of 10 mm/s.

4. Conclusions
A high capacity and efficiency of electron-beam mounts allows obtaining hardened layers of large thickness on large-sized items made of carbon and low-alloyed steels. This method allows to create high-carbon layers with thickness up to 2.7 mm. The main structural components of the deposited layers are: ledeburite, perlite and widemanstatten type secondary cementite.

The best quality of high-carbon layers on curved surfaces by electron-beam partial melting of carbon fiber fabrics were obtained using phenol-formaldehyde glue as a binder.

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