Structure and properties of steel case-hardened by non-vacuum electron-beam cladding of carbon fibers

A A Losinskaya, E A Lozhkina and A I Bardin
Novosibirsk State Technical University, 20, K. Marksa Prospekt, Novosibirsk, 630073, Russia

E-mail: alexeixxxx13@yandex.ru

Abstract. At the present time, the actual problem of materials science is the increase in the steels performance characteristics. In the paper some mechanical properties of the case-hardened materials received by non-vacuum electron-beam cladding of carbon fibers are determined. The depth of the hardened layers varies from 1.5 to 3 mm. The impact strength of the samples exceeds 50 J/cm². The wear resistance of the coatings obtained exceeds the properties of steel 20 after cementation and quenching with low tempering. The results of a study of the microhardness of the resulting layers and the microstructure are also given. The hardness of the surface layers exceeds 5700 MPa.

1. Introduction
Year by year, the requirements of the industry for utilizable materials are becoming higher that requires a constant search for the ways to improve materials performance characteristics. To improve the mechanical properties of the surface layers of products, surface hardening technological processes are used. It is possible to change the physical and mechanical properties, as well as the chemical composition of the surface layers. The most economical and widespread method of case-hardening of steel items is the cementation process. The main disadvantage of this process is its long duration, due to the need for a long diffusion saturation of the surfaces of items with carbon.

Alternative solutions to harden the steel surfaces are technologies based on the use of high-energy methods of action. Such methods make it possible to accelerate significantly the hardening process. In the modern literature there are data on the formation of hardened layers using laser, ion, electron, and plasma treatment [1-3]. For example, a plasma-electrolytic treatment process was used to carburize iron to a depth of 20–160 μm and formed a structure with a mixture of martensite, austenite, and cementite [4]. At the moment, the physics of high-energy treatment is well studied [5]. These methods are widely used in industry, providing coatings with high values of hardness, corrosion resistance, wear resistance and heat resistance. The technology of non-vacuum electron-beam processing is of great interest in the problem of creating high-strength coatings [6].

In previous studies, it was found that non-vacuum electron-beam treatment is an effective method to create high-carbon coatings on steels using carbon-containing powders [6]. In this paper, carbon fibers are used as a carbon source.

2. Methods
In this study, using non-vacuum electron-beam treatment of carbon fiber GG 210-P, high-carbon
layers were formed on low-carbon structural steel 20 using an industrial electron accelerator ELV-6 (property of the Institute of Nuclear Physics of the SB RAS). The merit of the non-vacuum electron-beam impact is that the kinetic energy of the electron beam formed in a vacuum is discharged into the air atmosphere and converted into a thermal energy in the processing zone.

For an even distribution of carbon in the base material, a wetting agent (an extra-pure grade iron powder) was used. The average powder particle size was 64 μm. To protect the melt bath and powder materials from the air exposure, the flux MgF₂ was used. The glue was used to prevent the blowing of the powders from the surface of the material by the shock wave of the electron beam. A mixture of a binder with iron and flux powders was applied in two ways. The first method consisted in applying the mixture over two layers of fiber, the second method was supplemented by applying a mixture between the fiber layers. Composition of the cladded material was the following: 13 wt.% of carbon, 37 wt.% of iron and 50 wt.% of flux, 100 wt.% of glue. Before cladding, the surface was cleaned of oxides and degreased. After surfacing, the workpieces were dried in a furnace at 40 °C till the glue completely dried out.

The top surface of each workpiece during electron-beam treatment was at a distance of 90 mm from the outlet. The energy of the electron beam was 1.4 MeV, the beam current was 8 and 10 mA. The electron beam was extracted into the atmosphere through a diaphragm of 1 mm diameter. Under these conditions, the Gaussian diameter of the electron beam on the specimen surface was 12 mm. The treatment took place in a track mode, with a speed of 10 and 25 mm per second.

The structural, mechanical, and tribological properties of the obtained materials were studied. Chemical composition of the cladded layers was determined on an ARL 3460 optical emission spectrometer. Studies of the structure of the samples were performed using a Carl Zeiss EVO50 XVP electron-scan microscope in the magnification range from ×50 to ×30 000. The specimen were etched using a 3% solution of nitric acid in ethanol. The microhardness of the coatings to be tested was evaluated using a WolpertGroup 402MVD semiautomatic micro microhardness tester in accordance with GOST 9450-76. Impact toughness testing of materials with cladded coatings was carried out on the impact pendulum-type testing machine Metrocom in accordance with GOST 9454-78. The maximum energy of the pendulum was 300 J. The tests on wear resistance in condition of friction on fixed abrasive particles were carried out in accordance with GOST 17367.

3. Results and discussion

As a result of cladding, layers with the thickness up to 3 mm with a carbon content of 2.2% were obtained. The study of the samples structure revealed the following structure: the upper high-carbon layer, the heat affected zone, the zone of the base unchanged metal. Perlite, secondary cementite and ledeburite are observed in the structure of the upper layer (Figure 1). The phase of secondary cementite has a Widmanstatten morphology. The heat affected zone consists of perlite and ferrite of the Widmanstatten type. Macroscopic defects (cracks, pores) were not found in the processed samples.

The maximum microhardness of the coatings obtained reaches 5700 MPa. The obtained values of the microhardness of the cladded layers are lower than that of the steel 20 cemented and hardened by the traditional method. The hardness of the cladded layers can be increased by using a subsequent heat treatment, which can also be carried out on an industrial electron accelerator.

The samples of steel 20 with a ferrite-pearlite structure are characterized by the highest impact strength (125 J/cm²). After electron-beam cladding, the impact toughness of steel 20 with high-carbon layers is 2.5 times lower compared to the initial unhardened state. It has also been experimentally established that the impact strength of the materials being studied depends to a greater extent not on the carbon content but on its thickness of the coatings.
Figure 1. The structure of cladded layer.

Figure 2. Fracture pattern, obtained in the impact toughness testing: a) general view; b) the fracture of the main material; c) fracture of the cladded layer.
Fractographic studies of the samples after impact toughness testing showed that the destruction of the base material corresponds to the viscous nature of the fracture (Figure 2a, b). The upper part of the fracture is the result of the brittle fracture; the lower part is ductile fracture by means of the micropores fusion. In Figure 2b, c, it is seen that the pits of ductile fracture of the base material are oriented in the direction of shear. Quantitative analysis showed that the size of the pits is in a wide range of sizes (from 1 μm to 20 μm).

The study of coatings obtained with non-vacuum electron-beam cladding of a powdered carbon-containing mixture showed that in most cases coatings are fractured by a brittle mechanism (Figure 2c).

The ability to operate under abrasive wear is one of the most important qualities of the case-hardened materials. Friction tests on fixed abrasive particles simulate the conditions that arise when the monolithic rock interacts with machine parts and structural elements. This type of wear is one of the most severe types of surface loading.

Tribotechnical testing showed that when exposed to fixed abrasive particles, the wear resistance of the cladded layers corresponds to the properties of steel 20 after cementation with quenching and low tempering (Figure 3).

![Figure 3. The results of the wear testing.](image)

The hardness of the cladded layers corresponds to the results of Ref. [1] and others in the cases where laser or plasma coatings had hypoeutectic or eutectic structure. Analysis of the microhardness distribution across the thickness of the hardened layer shows that the width of the transition zones within which the microhardness decreases to that of the substrate is ~200…250 μm. Thus, the most significant structural changes, associated with a decrease in microhardness, occur in a layer with a thickness of about 10…15% of the total thickness of the hardened layer.

4. Conclusion

The results of the executed work show that electron-beam cladding of carbon fibers in the air atmosphere is an effective way to obtain hardened high-carbon layers on steels. This technology ensures the formation of high-carbon layers up to 3 mm thick, which have high hardness and wear resistance. High-carbon layers are inextricably linked to the substrate and exert an embrittlement on the starting material, which is revealed during dynamic impact toughness testing.
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