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Surface hardening of steels with carbon by non-vacuum electron-beam processing

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ABSTRACT

Surface layers containing ~1.57–2.55% (wt) carbon were produced by atmospheric electron-beam cladding of low carbon steel plates with an iron–graphite powder mixture. The main process parameter determining the thickness, structure, and mechanical properties of the hardened layer was the electron-beam current. As the beam current was increased from 20 to 26 mA, the thickness of the cladding layers increased from 1.2 to 2.6 mm and the hardness decreased from 5.7 to 4.5 GPa. In friction tests against fixed abrasive particles, the wear-resistance of the cladding layers was close to the wear resistance of pack-carburized specimens. In electron-beam cladding of steel plates 10 mm thick with the powder mixture with electron-beam scanning over the plate surface, the cooling rate of the surface layer was less than the critical value, which made it impossible to obtain a martensitic structure. The main structural components in the cladding layers were ledeburite, secondary Widmanstätten cementite, and pearlite. To produce a high-carbon martensitic structure directly during cladding by enhancing the heat transfer to the colder volume of the workpiece, it is necessary to increase the thickness and mass of the workpiece or reduce the thickness of the hardened layer. Saturation with carbon and quenching of the cladding layer can be performed successively using the same electron accelerator.

1. Introduction

One of the simplest, most economical and effective method of hardening of steel parts is the diffusion saturation of their surface layers with carbon [1]. In the technical literature, this process is called carburizing. There are various methods for introducing carbon into the surface layers of steel articles under factory conditions. Carburizing is carried out in various solid, liquid and gaseous media [1] which act as carbon sources. Articles subjected to carburizing are usually heated above the point A_{C3} (in the temperature range from 910 to 930 °C, in some cases, to 1050 °C). At these temperatures, steel is in the austenite state. Saturation of the surface layers of articles with carbon occurs by a diffusion mechanism.

Usually, carburizing is combined with subsequent quenching and low-temperature tempering. Carburizing is used for low-carbon steels containing about 0.1–0.2% C, characterized by high ductility and low hardness, strength, and durability. The mechanism of steel hardening by carburizing and subsequent quenching involves the formation of a high-carbon martensite structure with high hardness in the surface layers. A hypereutectoid structure is formed (pearlite and secondary cementite) during the carburizing in the layer located closer to the workpiece surface. After quenching and low-temperature tempering, a tempered martensite with globular cementite inclusions is formed in this layer. This structure improves the wear resistance of the material under different wear conditions. In this case, the core of the steel article has increased toughness while remaining low-carbon.

Despite the advantages noted above, the carburizing process also has disadvantages. One of these is low productivity and high energy consumption of the process. The formation of hardened layer 0.5–2 mm thick requires carburizing for 6–8 h or more. Another drawback is that the technological capabilities of carburizing methods are limited by the dimensions of the thermal equipment. Many large articles requiring hardening cannot be placed in existing furnaces. The design and operation of carburizing equipment for large articles are not economically rational. An effective solution to this problem is the cladding of the surface of an article with a hard material. There are many methods for cladding with high-wear-resistant materials. These are, first of all, laser [2–8], electron-beam [9–12], plasma [13,14], and electric-arc [15] cladding processes. The technology of surface hardening of steels using electron beams extracted into air is worthy of special mention. This technology, implemented at powerful industrial accelerators produced at the Budker Institute of Nuclear Physics (Novosibirsk), provides high-performance cladding of steel products with durable materials [10,11] and surface hardening of steel [16,17].

The powder mixtures used for cladding typically contain carbides, nitrides, boron and various borides. This makes it possible to produce surface layers of complex compositions, hardened with high-strength

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particles. Both published data and the results of our studies show that carbon can be used as a cladding material in these processes. Saturation of the surface layers of steels with carbon is carried out using laser [2–8] and plasma cladding [14] and electrocontact thermochemical treatment [18]. Some of these methods are also often called laser surface alloying [3,5,7,8] or selective case hardening [14]. Carbon for cladding is commonly used in the form of graphite [2–8,14]. However, a number of studies have demonstrated the possibility of using carbon nanotubes for alloying [6,19], which has some advantages but is impractical due to the high cost of nanotubes.

The aim of this work was to study the surface hardening of low carbon steel plates by remelting a powder mixture containing graphite using electron beams extracted into the atmosphere.

2. Materials and methods

The workpieces were 100 × 50 × 10 mm plates of low carbon steel (0.19% C, 0.47% Mn, 0.20% Si, 0.009% P, 0.042% S, 0.15% Ni, 0.15% Cu). The powder mixture for cladding consisted of graphite, carbonyl iron and a flux which protected the melt from oxygen. Magnesium fluoride (MgF_2) was used as a flux. In the powder mixture, the flux content was 50% (wt), and the concentrations of iron and graphite were 25% (wt) each. The iron powder mixed with graphite provided the preservation of carbon and its more uniform distribution in the surface layer. Before cladding, the powder mixture was uniformly spread over the surface of the steel workpiece in an amount of 0.2 g per 1 cm^2. The cladding process was performed in an ELV-6 electron accelerator [9–12]. The electron-beam energy was 1.4 MeV. The beam current was varied in the range of 20–26 mA. The electron beam was extracted into the atmosphere through a diaphragm of 1 mm diameter. The distance from the beam outlet to the workpiece was 90 mm. Under these conditions, the Gaussian diameter of the electron beam on the specimen surface was 12 mm. The longitudinal speed of the specimen relative to the outlet was 10 mm/s. The main modes of cladding are presented in Table 1. The beam was scanned with an electromagnetic scanner to increase the performance of the treatment (modes 1–4). The peak-to-peak value of the scanning electron beam was the same as the sample width and was equal to 50 mm. The high scanning frequency (50 Hz) provided uniform exposure of the sample area to the beam (Fig. 1). One of the workpieces was processed with an electron beam without scanning the surface to reduce the amount of molten material, reduce the amount of heat introduced into the workpiece, and increase the cooling rate of the cladded layer (mode 5). The workpiece was moved in the longitudinal direction at a speed of 10 mm/s relative to the beam, and the beam current was equal to 6 mA.

Chemical composition of the cladded layers was determined on an ARL 3460 optical emission spectrometer. The structure of the materials was studied using optical metallography (Carl Zeiss Axio Observer Z1m microscope), scanning electron microscopy (Carl Zeiss EVO 50 XVP microscope), transmission electron microscopy (Tecnai G2 20 TWIN microscope), and X-ray diffraction (ARL X'TRA θ–θ diffractometer). Diffraction patterns were taken using Cu Kα radiation. The specimen surfaces were scanned in a step-scan mode ($\Delta 2\theta = 0.02°$) with a dwell time of 5 s per point. Metallographic microsections were made by mechanical grinding and subsequent polishing. The structure of alloys was etched using a 3% solution of nitric acid in ethanol. The preparation of foils for transmission electron-microscopic studies included cutting of flat specimens, grinding of sample to a thickness of 0.1 mm, and dimple grinding on a Gatan Dimple Grinder and ion thinning on a Gatan PIPS 659 ion mill.

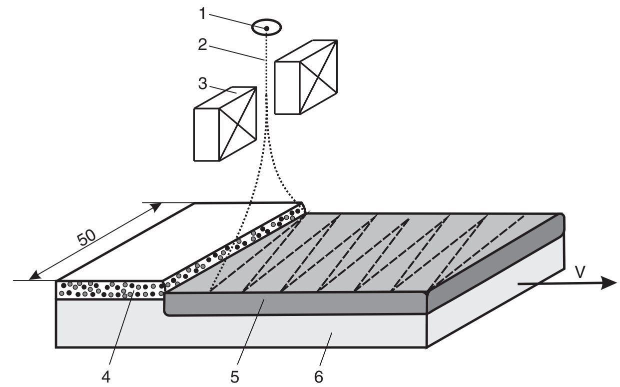

Fig. 1. Schematic diagram of non-vacuum electron-beam cladding of steel plate with the iron–graphite powder mixture. 1—Outlet, 2—electron beam, 3—electromagnetic scanning device, 4—powder mixture of graphite, iron, and flux, 5—cladding layer, 6—steel substrate.

Microhardness was measured on cross sections using a Wolpert Group 402 MVD microhardness tester at an indenter load of 0.98 N. To estimate the embrittlement of steel by the cladding layers the Charpy V-notch test was carried out. The scheme of the test was previously used in Ref. [20].

The wear resistance of the cladding materials was investigated in friction tests against fixed abrasive particles (GOST 17367-71). The test specimens had a cylindrical shape 2 mm in diameter and 10 mm high. During the tests, the specimens were pressed with a power of 3 N against an abrasive cloth rotating at a rate of 100 rpm and were simultaneously moved in the radial direction. The trajectory of the specimens with respect to the abrasive cloth had the shape of the Archimedes spiral. Neighboring tracks did intersect each other. The abrasive material was silicon carbide with particle sizes of 80 to 100 μm. The duration of the tests was 35 s.

3. Results and discussion

The melting of the materials in an oxidizing medium, low density of graphite and the high rate of its heating suggested that under a brief exposure to a high-power electron beam, the carburizing process may not be sufficiently effective. Expected problems were related to the possible oxidation of carbon and ejection of the graphite powder with the formation of a gas cloud during rapid heating of the material. Nevertheless, chemical analysis and structural studies showed that the electron-beam melting of the powder mixture and the substrate material resulted in the formation of surface layers with increased carbon content. According to atomic-emission spectrometry data, the carbon content in the layers melted by the electron beam was 1.57–2.55% (wt) (Table 1).

Table 1
Modes of non-vacuum electron-beam cladding (beam electron energy—1.4 MeV, diameter of the electron spot on the surface—12 mm, speed of movement—10 mm/s).

Mode number	Beam current, mA	Transverse scanning	Specific surface energy kJ/cm^2	Thickness of the cladding layer, mm	Maximum carbon content, % (wt)	Weight loss of powder mixture, including the weight of slag (flux),%
1	20	Yes	5.6	1.2	2.55	77
2	22		6.2	1.3	2.27	75
3	24		6.7	2.0	2.19	73
4	26		7.3	2.6	1.57	75
5	6	No	7.0	–	–	–