Boron electroexplosive alloying of austenite steel

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Abstract. Studies of phase and elemental composition, defect substructure of surface layer of Cr18Ni10Ti stainless high chromium steel subjected to alloying by electroexplosion method were performed by techniques of X-ray structural analysis, optical and electron microscopy. Titanium and boron were chosen as alloying elements. It has been stated that electroexplosion alloying of steel results in the formation of surface layer having a multiphase submicronanocrystalline structure being characterized by the presence of micropores, microcracks and microcraters. Dependence of phase composition and microhardness of surface layer on relation of titanium and boron masses at electroexplosion alloying has been revealed. It has been found that microhardness of the modified layer is determined by relative masses of titanium borides’ fractions in the surface layer of steel and it may increase 18-fold that in the initial (prior to electroexplosion alloying) state.

1. Introduction

Nowadays, boriding is one of the most promising methods of chemical and thermal treatment of metals and alloys, including steels [1]. The most common types for industrial application are the boriding techniques including saturation in gaseous, liquid and solid media. The process of liquid nonelectrolyzed boriding which permits one to design one-or multi-phase structure of surface layer and give the prescribed properties to the core (from annealed to hardness state) [2] is perspective for use. The methods of thermocycle boriding [3], electron beam boriding [4] and boriding with application of laser beams [5] are being at the stage of development. The given technique of boriding, by its mechanism, is a modification of boriding from solid phase saturating coatings under chemical and thermal treatment [4].

The most uniform and homogeneous penetration of boron into the surface layer of metal is realized when method of gas boriding. Boriding of parts is performed in medium of gases containing oxides, halogenides and hydrogen compounds of boron. Atomic boron, being liberated in thermal decomposition of gases, deposits on the surface of parts and diffuses deep into metal. Nevertheless, boriding mixtures of gases being formed are dangerously explosive that imposes restrictions to the application of this technique. The limited use of boriding in powders and pastes is caused by high labour consumption and high costs of the processes and difficulty associated with formation of definite structure and phase composition of the hardened layer and properties of core.

In the past few decades the modification methods of metals and alloys based on application of concentrated fluxes of energy [6] are actively developed. One of these methods is electroexplosive alloying. Electroexplosive alloying (EEA) of surface of metals and alloys is based on the phenomenon
of failure of conductor under the action of powerful pulses of electric current [7]. Plasma stream, formed from products of electric explosion of a conductor, melts the surface being treated, while saturating a melt by components of plasma jet. Subsequent high-speed cooling caused by removal of heat into the bulk of material results in self-hardening of modified layer. Powdered weighed samples of various substances may be placed into the area of conductor explosion (current carrying foil). They are transported to surface being hardened by plasma stream providing additional modification of structure and properties of a material [8]. EEA is characterized, in most cases, by substantial overheating of surface being hardened, above boiling temperature due to high pressure of jet on a surface that is accompanied by formation of high developed relief with a large number of microdroplets, microcraters, microcracks, metal burrs. Electroexplosive alloying, due to little time of thermal effect, is characterized by high rate of cooling of material’s modified layer. In consequence of it, a submicro-nanocrystalline structure [9] is formed in a surface layer.

The paper is concerned with the analysis of results and establishing the regularities of structure and properties, formation of Cr18Ni10Ti stainless high chromium steel subjected to electroexplosive alloying with titanium and boron.

2. Material and methods
Stainless steel Cr18Ni10Ti (Standard 5632-72) [10] was used as material under study. The samples had the shape of plates 10x10x5 mm in size. At the first stage the processing of steel surface was performed by method of electroexplosive alloying (EEA) at device EVU 60/10 [11]. Foil of commercially pure titanium VT1-0 was used as current-carrying material. The weighed sample of boron powder was placed on surface of the foil. Powder of amorphous boron (B-99D- Technical Specifications 1-92-1549, B>99%, diameter of particles 0.5-5 µm). Parameters of electroexplosive alloying were the following: power density and duration of plasma pulse effect 2.2 GW/m² and 100 µs. Four modes of EEA were used that differed in foil mass of titanium and powder mass of amorphous boron (table 1).

| mode | m (Ti), mg | m (B), mg | m (Ti) / (B) |
|------|------------|------------|--------------|
| 1    | 360.7      | 50         | 7.214        |
| 2    | 392.2      | 62.5       | 6.275        |
| 3    | 423.7      | 75         | 5.649        |
| 4    | 455.2      | 87.5       | 5.202        |

Study of steel structure in the initial state and after modification was performed by the methods of X-ray structural analysis (diffractometer XRD 600), optical (device Microvisor Viso – MET – 221) and scanning electron (device SEM 515 Philips) microscopy. Examination of samples’ elemental composition was carried out by the methods of microspectral analysis. The properties of the modified layer were characterized by determining microhardness (microhardometer PMT-3, indenter load 1 N).

3. Results and discussion
As it was shown in research carried out earlier [7-9, 11] electroexplosion processing of metals and alloys including steels is accompanied by formation of highly developed relief with a large number of microdroplets, microcraters, microcracks and metal burrs. Characteristic image of surface structure of steel being formed in electroexplosion alloying with titanium and boron is shown in figure 1. Diverse defect structure of modification surface is clearly seen: metal burrs (figure 1, a), microcracks (figure 1, b), micropores (figure 1, c). Electroexplosion alloying, due to little time of thermal effect, is characterized by high cooling rate of material’s modified layer. As a consequence, the submicro-nanocrystalline structure whose characteristic image is presented in figure 1, d is formed in the surface layer. The structural analysis of steel surface being formed in electroexplosion alloying clarifies the formation of the material with crystallites’ sizes of 50-70 nm (figure 1, d).
The studies of elemental composition of steel layer subjected to electroexplosion alloying were performed by methods of micro-X-ray spectral analysis. The characteristic image of steel surface portion and energy spectra obtained from it is depicted in figure 2. It is clearly seen (figure 2, b) that on the picture of energy spectra the maximums of both main elements of steel (Fe, Cr, Ni) and alloying elements (B, Ti) are present. The latter lends support to the statement that electroexplosion alloying is accompanied by saturation of steel surface layer with elements of electroexploded foil (Ti) and powder (B) placed on it.

The quantitative analysis results of elemental composition of Cr\textsubscript{12}Ni\textsubscript{18}Ti\textsubscript{10} steel surface layer subjected to electroexplosion alloying are shown in table 2. When analyzing the results presented in table 2 it may be noted that boron and titanium are the main elements of steel surface layer; the elements forming steel are present in negligible quantity. Maximum quantity of boron and titanium atoms is revealed in steel surface layer modified by electroexplosion method according to mode 3. The relative content of steel elements (iron, chromium, nickel) is little in surface layer. Therefore, electroexplosion processing with parameters selected in the research is accompanied by formation of not only steel alloyed layer but also a thin coating based on titanium and boron.
elemental composition of sample’s portion are set out in table 1; EEA according to mode No. 1; scanning electron microscopy.

**Table 2.** Micro-X-ray spectral analysis results of Cr$_{18}$Ni$_{10}$Ti steel surface layer subjected to EEA with titanium and boron. EEA models are designated by numbers in Table (corresponding to table 1).

| Element | No. 1 | No. 2 | No. 3 | No. 4 |
|---------|-------|-------|-------|-------|
| B(K)    | 49.39 | 41.35 | 21.80 | 18.81 |
| Ti(K)   | 46.94 | 32.97 | 43.96 | 71.03 |
| Cr(K)   | 0.32  | 4.59  | 5.84  | 0.73  |
| Fe(K)   | 0.21  | 18.31 | 25.0  | 8.43  |
| Ni(k)   | 0.44  | 2.78  | 3.41  | 0.00  |

Phase composition of steel layer modified by electroexplosion method was studied by methods of X-ray structural analysis. The portion of X-ray diffraction pattern from steel surface layer subjected to electroexplosion alloying according to mode No. 1 is depicted in figure 3.

![Figure 3. Portion of X-ray diffraction pattern obtained from steel surface layer subjected to EEA according to mode No. 1.](image)

The quantitative X-ray phase analysis results of steel surface layer subjected to electroexplosion alloying with different relations of titanium and boron masses are presented in table 3.

Analysis of the results shown in table 3 testifies that electroexplosion alloying of steel (independent of alloying parameters) is accompanied by formation of multiphase surface layer whose main phases are titanium borides TiB and TiB$_2$, the total content of which is maximum in the sample processed according to mode No. 1. These results are in good agreement with micro-X-ray spectral analysis results of steel surface layer presented in table 2 and demonstrating the maximum quantity of titanium and boron precisely in the sample processed according to mode No. 1.

Mechanical properties of steel surface layer modified by electroexplosion alloying were characterized by microhardness. The obtained results are shown in table 4. When analyzing the results of table 4 it can be noted that EEA is accompanied by multiple (5.2-18.1-fold) increase in microhardness of steel surface layer, independent of treatment mode. Maximum increase in microhardness of steel surface layer is obtained for samples modified according to mode No. 1. When
comparing the results of elemental and phase composition of the modified layer presented in table 2 and table 3 with the results of mechanical tests (table 4) it can be stated that maximum hardness of steel surface layer corresponds to maximum concentration of boron in the layer and maximum relative content of titanium borides TiB and TiB2.

### Table 3. X-ray phase analysis results of Cr18Ni10Ti steel surface layer subjected to electroexplosion alloying with titanium and boron.

| EEA mode | Phase | Mass. | Parameters of lattice, nm | D(coherent scattering region), nm | ∆d/d, 10^3 |
|----------|-------|-------|---------------------------|----------------------------------|------------|
|          |       |       | a | b | c |                          |                |
| No. 1    | TiB   | 61.25 | 0.42516 |                  | 29.3 | 1.213 |
|          | TiB2  | 13.69 | 0.30193 | 0.32448 | 16.7 | 0.597 |
|          | γ-Fe(Ni) | 2.02 | 0.35866 |                  |      |        |
|          | TiNi  | 18.87 | 0.75437 | 0.51849 | 10.5 | 7.747 |
|          | β-Ti  | 4.17  | 0.32136 |                  | 23.28 | 6.443 |
|          | TiB   | 44.07 | 0.42587 |                  | 24.9  | 1.153 |
| No. 2    | TiB   | 1.78  | 0.30318 | 0.32231 | 10.2  | 4.992 |
|          | TiFe2 | 41.17 |                  |                          |        |
|          | Ti0.05Cr0.05 | 12.98 |                  |                          |        |
|          | TiB   | 23.73 | 0.42804 |                  | 42.9  | 2.133 |
| No. 3    | TiFe2 | 29.34 | 0.48626 | 0.79119 | 31.4  | 2.317 |
|          | FeNi  | 1.72  | 0.35840 | 0.35368 | 9.3   | 6.687 |
|          | TiNi  | 43.46 | 0.30148 |                  | 86.6  | 32.27 |
|          | β-Ti  | 1.75  | 0.32808 |                  | 398.5 | 1.992 |
|          | TiB   | 51.59 | 0.42513 |                  | 27.1  | 2.443 |
|          | FeNi  | 0.82  | 0.34975 | 0.35081 | 37.8  | 1.23  |
| No. 4    | α-FeNi | 0.44 | 0.28776 |                  | 30.2  | 0.91  |
|          | γ-Fe(Ni) | 0.35 | 0.35056 |                  | 33.6  | 3.21  |
|          | TiCr2 | 9.96  | 0.49610 | 0.80199 | 61.9  | 0.916 |
|          | Ti0.05Cr0.05 | 12.42 | 0.46076 | 0.27584 | 37.8  | 2.059 |
|          | α-Ti  | 24.41 | 0.29528 | 0.47549 | 10.6  | 6.561 |

### Table 4. Microhardness of Cr18Ni10Ti steel in initial state and after electroexplosion alloying (δ(HV) – measurement error).

| Treatment mode | HV, MPa | δ(HV), MPa |
|---------------|---------|------------|
| Initial       | 1952.0  | 970        |
| No. 1         | 35398.4 | 15564.4    |
| No. 2         | 10243.4 | 2638.4     |
| No. 3         | 11144.0 | 3373.9     |
| No. 4         | 18993.9 | 1361.4     |

### 4. Conclusion

Surface alloying of Cr18Ni10Ti high chromium stainless steel with boron and titanium atoms by electroexplosion method has been performed. Studies of phase and elemental composition, defect substructure of steel modified layer by methods of modern materials science (scanning electron microscopy, X-ray structural and micro-X-ray spectral analysis) have been carried out. It has been stated that electroexplosion alloying of steel results in formation of surface layer having the multiphase submicro – nanocrystalline structure being characterized by presence of micropores, microcracks and microcraters. Dependence of phase composition and microhardness of surface layer on relation of boron and titanium masses at electroexplosion alloying has been detected. It has been suggested that electroexplosion alloying with parameters selected in the research is accompanied by not only steel alloying but also formation of thin coating enriched by titanium and boron atoms. It has been found that microhardness of the modified layer is determined by relative mass of titanium.
borides’ fractions in steel surface layer and may increase by more than 18 times that of steel in the initial (prior to electroexplosion alloying) state.

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