Formation of wear-resistant chromium-vanadium cast iron coating using a continuous and pulsed electron beam

N V Tatarkina¹, A I Ziganshin², B V Dampilon¹², V G Durakov² and A M Tolstokulakov¹

¹Tomsk Polytechnic University, Tomsk, Russia
²Institute of Strength Physics and Materials Science, Tomsk, Russia

E-mail: dampilon@ispms.tsc.ru

Abstract. The paper reports the results of an investigation of structure formation in the eutectic chromium-vanadium cast iron coating deposited by electron-beam hardfacing (EBH) and subjected to multipoint pulsed electron-beam treatment (MPEBT) of the surface layers. The coating material structure in the zones modified by MPEBT changes considerably, showing the presence of a large amount of supersaturated austenite matrix and eutectic colonies in the form of fine isolated inclusions. The eutectic colonies are fan-like. The leading phase in the eutectic colonies is vanadium carbide. After aging within the temperature range from 900 to 1100°C the structure of the modified zones exhibits a large amount of fine secondary carbides Cr₇C₃ rejected from the matrix. The secondary carbides are uniformly distributed in the bulk of the modified zones. The matrix after aging undergoes \( \gamma \to \alpha \) transformation and mainly has the martensitic structure. Aging increases significantly the hardness of the modified zones and abrasive wear resistance of the entire coating.

1. Introduction

Today, more and more structures, constructions and equipment used in various industries (power engineering, transport, oil and gas production, mining) work in the conditions of high contact loads accompanied by abrasive and impact-abrasive wear, which raises a widespread problem of machinery breakdown.

A primary task in this situation is to provide long and cost effective service life and reliability of working parts of machines, technological equipment and tools as these factors are directly related to the enhancement of wear resistance.

Currently, new methods of materials production have been intensively developed and applied. These are the technology of very rapid melt cooling during coating deposition or production of solid materials, dispersion, thermomechanical treatment, ultrasonic treatment, ultrafast deformation, synthesis, and so on. A combination of these technologies often allows new structural and functional materials to be designed [1-3].

The development of a method for producing materials with high structural homogeneity and fine strengthening phases from a highly nonequilibrium structural state using rapid melt crystallization and subsequent aging opens up new possibilities for hardening of materials. Rapid melt crystallization results in the formation of nonequilibrium structural states, supersaturated solid solutions, new metastable phases and structures. Subsequent aging leads to the rejection of a large amount of fine
secondary strengthening phases from a supersaturated solid solution with the formation of a homogeneous material structure. The given method thus requires the study of the features and regularities of structure formation and phase transformations in such materials and coatings.

A promising method for a limited production of materials with high structural homogeneity and fine strengthening phases can be a complex electron-beam technology which includes electron-beam hardfacing in vacuum and multipoint pulsed electron-beam treatment [4] with subsequent heat treatment (artificial aging).

This paper reports the results of an investigation of structure formation in modified zones produced by MPEBT on the surface of chromium-vanadium cast iron coatings.

2. Materials and experimental procedure
Coatings of eutectic chromium-vanadium cast iron with rated chemical composition 2.5C, 17Cr, 5V, 1Si, 1Ni, 1Mn, Feres. (mass %) were deposited by electron-beam hardfacing in vacuum on low-carbon steel substrates measured 350×35×5 mm. The thickness of the deposited coatings was 3 mm. After polishing (down to 2 mm) the coating surface was locally treated at certain intervals (Fig. 1) by a pulsed, point-focused electron beam (21 mm). After the treatment the entire coating surface was covered by modified zones with discrete point distribution in a square packing. The diameter of each zone was about 1000 μm and the depth was 600 μm. Depending on the electron beam power and focusing, the zones can be hemispherical or conical in cross-section. Each modified zone was formed by one electron beam pulse of duration 15 ms and power density 56 kW/cm². Heat treatment of specimens by “aging” was carried out in a vacuum furnace at temperatures 900, 1000 and 1100°C within 30 minutes of exposure. The rate of heating up to the holding temperature and subsequent cooling down to 500°C was 15°C/min. X-ray phase analysis of the modified zones was performed using an X-ray diffractometer Shimadzu XRD 6000. X-ray spectral microanalysis was performed using a microscope Leo Evo 50. The hardness of the modified zones was measured on the Nanotest system.

3. Results and discussion
The micrograph of the chromium-vanadium cast iron coating surface with modified zones produced by MPEBT is given in Fig. 1b. Between the modified zones there are coating regions not subjected to MPEBT which provide for stress relaxation.

Metallographic analysis has revealed considerable microstructural changes that occurred in the coating after MPEBT (Fig. 2).
As distinct from the initial state (after hardfacing) (Fig. 2a), the structure of the modified zones is highly homogeneous due to a uniform distribution of fine (up to 3 μm) inclusions of round shape (Fig. 2b) observed as fan-like eutectic colonies on the high-power micrograph in Fig. 3a. Vanadium carbides are the first precipitates that are formed from the melt and make up eutectic colonies for the short lifetime of the melt during the electron beam pulse, being the nucleation centers of the colonies (Fig. 3b).

X-ray structure analysis results (Fig. 4) demonstrate that the matrix of the deposited coating consists of austenite (25 %) and martensite (30 %), and the carbide phase is represented by carbides M₇C₃ (28 vol. %), VC (12 %) and V₂C (5 %). After MPEBT the material of the modified zones consists mainly of austenite (60 vol. %) and vanadium carbide VC (25 %) which is the leading phase in the eutectic colonies (Fig. 3b). Evidently, a liquid phase is formed in the coating material in the zone heated by the electron beam for pulse time 15 ms which is immediately crystallized when the electron beam is turned off. Vanadium carbides are the first precipitates that are formed from the melt and make up fine fan-like eutectic colonies for the lifetime of the liquid phase.
X-ray spectral microanalysis of the eutectic colonies shows that in the center of the colonies there are particles containing on average up to 60 mass % V, 15 % Cr and 7 % Fe. Although most of the colony falls within the zone of identification, the high vanadium concentration indicates that particles in the center of the colonies are vanadium carbides. The total volume fraction of carbides in the modified zones decreases from 45 to 30 vol. % (Fig. 5a) due to their partial dissolution in austenite. Correspondingly, the volume fraction of supersaturated austenite increases from 25 to 60 vol. %.

According to X-ray spectral microanalysis data, the modified zone matrix contains on average 17.68Cr, 3.64V, 0.56Si, 0.62Mn, 1.47Ni, 76.03Fe (mass %), and the initial coating matrix contains 11.12Cr, 1.47V, 0.66Si, 0.65Mn, 1.7Ni, 84.39Fe (mass %) (Table 1). It is shown that the chromium and vanadium concentration in the austenite matrix increases 1.6 and 2.5 times, respectively, as compared to the initial coating matrix. Hence follows that MPEBT leads to the formation of modified zones with highly nonequilibrium structural-phase state. The formed matrix consists of a large amount of metastable supersaturated austenite, which determines a reduced hardness of the modified zone (1.2 GPa) as compared to the initial coating hardness (5.7 GPa) (Fig. 5).

**Table 1.** X-ray spectral microanalysis data for the initial coating and the modified zone produced by MPEBT*.

| Chem. element | Matrix composition in the modified zone *, mass % | Matrix composition in the initial coating *, mass % |
|---------------|-----------------------------------------------|-----------------------------------------------|
|               | 1    | 2    | 3    | 4    | 5    | 6    | 7    |
| Si            | 0.55 | 0.56 | 0.52 | 0.6  | 0.64 | 0.66 | 0.68 |
| V             | 3.92 | 3.72 | 3.63 | 3.29 | 1.47 | 1.59 | 1.36 |
| Cr            | 19.22| 17.95| 17.66| 15.90| 11.45| 11.55| 10.37|
| Mn            | 0.69 | 0.6  | 0.64 | 0.56 | 0.61 | 0.62 | 0.72 |
| Ni            | 1.35 | 1.62 | 1.50 | 1.41 | 1.94 | 1.62 | 1.55 |
| Fe            | 74.27| 75.55| 76.05| 78.24| 83.89| 83.96| 85.32|

*—carbon not taken into account.
In order to reject secondary carbides from the supersaturated austenite matrix of the modified zones, the specimens were subjected to aging in the temperature range from 900 to 1100°C. It was established experimentally that during aging the volume fraction of carbides and martensite increases significantly in the entire temperature range (Fig. 4). For example, after aging from 1100°C the total fraction of carbides increased from 30 to 52 vol. %, martensite—from 10 to 39 vol. %, and the austenite fraction decreased from 60 to 9 vol. % as compared to the material subjected to MPBET. Investigations showed that during aging a large amount of fine carbides Cr$_7$C$_3$ is rejected from supersaturated austenite, while austenite undergoes $\gamma \rightarrow \alpha$ transformation with martensite formation. In this case, the structure is characterized by the presence of a large amount of fine (1–2 μm) secondary carbides and by their highly homogeneous distribution in the bulk of the modified zones (Fig. 2c). It is found that the increase in the volume fraction of carbides Cr$_7$C$_3$ and martensite as well as the decrease in the residual austenite fraction are accompanied by hardness growth (Fig. 5). The maximum hardness of 14 GPa corresponds to the modified zones with the highest fraction of carbides and martensite (aging at 1100°C). The decrease in the fraction of vanadium carbides after aging is evidently due to the fact that they became the nucleation centers of secondary carbides Cr$_7$C$_3$ formed on their surface.

The results of abrasive wear testing of the coatings (GOST 23.208-79 “Abrasive wear testing of materials in friction against non-fixed abrasive particles”, primary standard: steel 45, Kw = 1) are the following: the coefficient of relative abrasive wear resistance of the coated specimens is Kw = 0±0.7, for the coatings subjected to MPEBT Kw = 7±1.2 and to heat treatment (aging at 1100°C) Kw = 25±1. The reduced wear resistance of the specimens after MPEBT is, first, due to a high fraction of metastable austenite (60 vol. %) in the structure of the modified zones and, second, due to a relatively low hardness of the modified zones on the whole. The maximum wear resistance of the coatings is achieved after aging at 1100°C, as a result of the growing volume fraction of carbides (52 vol. %) and martensite (39 vol. %) in the modified zones.

**Conclusion**

1. Multipoint pulsed electron-beam treatment of the surface of chromium-vanadium cast iron coating leads to the formation of modified zones consisting mainly of metastable supersaturated austenite and fine isolated eutectic colonies of round shape fanning out from the colony centers with the leading VC phase.
2. Heat treatment (aging) in the temperature range from 900 to 1100°C within 30 minutes of exposure causes intensive rejection of fine secondary carbides Cr$_7$C$_3$ from supersaturated austenite uniformly
distributed in the modified zones, austenitic-martensite transformation and a significant increase in the hardness of the modified zones and abrasive wear resistance of the entire coating.

3. The complex technology including electron-beam hardfacing, multipoint pulsed electron-beam and subsequent heat treatment allows designing coatings with specified geometry and periodic distribution of modified zones on their surface.

References
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Authors:
1. Natalia V. Tatarkina, graduate student of the Department of Materials Science in Mechanical Engineering of National Research Tomsk Polytechnic University
2. Artem I. Ziganshin, 2/4, postgraduate student at Institute of Strength Physics and Materials Science of Siberian Branch Russian Academy of Sciences
3. Bair V. Dampilon, PhD, associate professor of the Department of Materials Science in Mechanical Engineering of National Research Tomsk Polytechnic University, research fellow at Institute of Strength Physics and Materials Science of Siberian Branch Russian Academy of Sciences
4. Vasily G. Durakov, PhD, senior researcher at Institute of Strength Physics and Materials Science of Siberian Branch Russian Academy of Sciences
5. Aleksey M. Tolstokulakov, student of the Department of Materials Science in Mechanical Engineering of National Research Tomsk Polytechnic University.