# CREATION WEAR-RESISTANT GRADIENT COATING ON THE BASED ON TITANIUM BORIDE SYNTHESIZED BY ELECTRON-BEAM SURFACING

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**Abstract**

*The paper presents the investigation results for the structure and properties of composite coatings obtained from a mixture of thermoreactive FeB and FeTi powders by electron beam surfacing. The dependence of the coating phase and structure formation on the granulometric composition of initial components of the fused mixture is shown. The abrasive wear resistance, friction coefficients and wear rate in friction pairs are studied. The relation of the obtained characteristics to the structure and morphological features of the coating structural components is demonstrated.*

**Key words:** *electron-beam surfacing in vacuum, composite coatings, thermoreactive powder, titanium diboride*

## 1. INTRODUCTION

The wear resistant composite coatings on the basis of titanium borides, which are synthesized from thermoreactive powder components of a boron-containing mixture at electron beam surfacing, are interesting for applications today.

It is known that in electron beam surfacing of thermoreactive powders an additional amount of heat is released in the fusion zone due to the exothermal reaction between the mixture components. This allows, with the same electron beam power, the deposition of coatings with a required content of the fine-grained refractory component. The physico-mechanical properties of the coatings can vary in a wide range depending on the proportion and sizes of initial components in the fused mixture. The coating structure formation ends with the convective mixing of solid-liquid melts, which have formed after the complete dissolution of components having different viscosity because of different chemical composition and different content of refractory particles in them [1]. The degree of the melt mixing depends on many factors, including the size of initial components. Obviously, changes in the granulometric composition of the fused powder would greatly affect the crystallization rate and completeness of phase transformations at electron beam surfacing, thus defining the microstructure, phase composition and service properties of deposited coating.

As known from metallurgical practice, the melt properties can significantly change after complex microalloying and modification. Such treatment neutralizes the negative effect of some detrimental impurities and can entirely change the structure and properties of the as-cast material. In multiphase as-cast alloys such admixtures as boron, calcium and europium increase the melt fluidity primarily owing to the dendritic structure refinement and, consequently, to a decrease in the temperature of the solid phase matrix formation [2]. However, the useful effect of modification on the coating structure and properties is not limited only to the degree of structure refinement and improvement of its homogeneity. It retards the coagulation of secondary phases at surfacing due to the formation of additional crystallization centers [3].

Thus, it is essential to determine the effective modifying elements that would provide the best combination of the structure and properties of coatings produced of thermoreactive Ti–B–Fe powders by electron beam surfacing in vacuum.

**The aim of the paper** is to study the simultaneous synthesis of boride compounds and formation of composite coatings on their basis under vacuum electron-beam treatment of thermoreactive powders.

And is to study the influence of amorphous boron and zirconia on the structure and phase composition of coatings based on refractory boride compounds synthesized under the electron beam.

## 2.MATERIALS AND EXPERIMENTAL PROCEDURE

The mixture for the electron beam surfacing of coatings and their further examination was prepared of low-cost thermoreactive ferroalloy powders FeB (grade FB-20) and FeTi (grade FTi65), amorphous boron (MRTU-602-292-14) and $ZrO_2$ powder widely used in steel and alloy metallurgy.

Chemical composition of ferroalloys (wt %) used in the study

Table 1

| Grade | B | Si | Al | C | S | P | Cu | Ti | V |
|---|---|---|---|---|---|---|---|---|---|
| FB-20 | 20 | 2 | 3 | 0,05 | 0,01 | 0.02 | 0.05 | – | – |
| FTi65 | – | 1 | 5 | 0.4 | 0.05 | 0.05 | 04 | 65 | 3 |

The composite material with a definite proportion of the refractory compound (titanium diboride) and metal binder (iron) was produced by the chemical reaction $xFeB + yFeTi \rightarrow TiB_2 + Fe + Q$.

The mixture composition was calculated so that to produce the $TiB_2$-Fe composite coating with 33 mass % of titanium diboride. The given percentage is provided by the proportion of the used mixture components FeB – FeTi = 1:1.

To study the features of the phase and structure formation in the fused layer, three variants of FeB – FeTi powder mixtures were electron-beam deposited in experiments. The mixtures differed in the granulometric composition of initial components: 1) FeB(50–125 μm)+FeTi(200–315 μm); 2) FeB(200–315 μm)+FeTi(200–315 μm); 3) FeB(200–315 μm) + FeTi(50–200 μm).

The coatings were electron-beam deposited on steel substrates (grade St.3) in 2–4 passes at accelerating voltage 28 kV. The beam diameter was 1.0 mm, scanning length 12 mm, and substrate velocity 2 mm/s. The fused layer thickness was 2–3 mm.

The phase composition was X-ray examined by a diffractometer DRON-4, the chemical composition was studied by a setup KAMEBAX-MIKROBEAM for X-ray spectrum microanalysis on an area of 1 μm. The coating microstructure was examined by a light microscope MIM-9. The hardness $H$ of the main structural components was measured by nanoindentation using a CSEM Nano Hardness Tester under load 5 g. The microhardness $H\mu$ was measured by a device PMT-3 under the load $P$ = 50 g.

The tribological properties of the coatings were studied in friction pairs consisting of a stationary pin of hard alloy VK-6 and rotating disc. The pin hardness was $H\mu$ = 29.3 GPa. The tests were performed at room temperature with and without lubrication (N20+SMT) of the contact zone by a PC-controlled high temperature tribometer THT-S-AX0000 under load 10 N and sliding velocities $V$ = 5 and

11 cm/s. The major wear parameters of coatings in the friction pair were determined by the stabilization of the friction coefficient and linear wear in the course of continuous sliding after running-in. The fractographic analysis of fracture surfaces obtained under shock loading was carried out using a scanning electron microscope REM-200.

## 3. EXPERIMENTAL RESULTS AND DISCUSSION

### 3.1. Coatings of thermoactive powder mixture FeB(50–125 μm)+FeTi(200–315 μm) (coating 1)

The comparative analysis has shown that the given coating has the most heterogeneous structure across the thickness. Fragments of the structure are depicted in Fig. 1. The structure is typically observed after the crystallization of melts of nonuniform concentration. The uneven microhardness distribution across the coating thickness clearly demonstrates its heterogeneity (Fig. 4,a).

The performed investigation suggests the following mechanism of structure formation at surfacing. First, FeTi particles of size 200–315 μm melt ($T_m$ = 1200°C) and form a ferrotitanium melt. When contacting with a conglomerate of FeB particles ($T_m$ = 1540°C), the melt forms a ring structure around the FeB particles due to the formation of low-temperature contact eutectics. The ring structure consists of titanium diboride crystals of hardness $H$ = 38 GPa (Fig. 1,b). The formation of the liquid phase — ferrotitanium melt — favors further refinement of the FeB particles that rapidly dissolve in the FeTi melt and saturate it with boron. The final coating structure is a result of the solidification of the two heterogeneous melts.

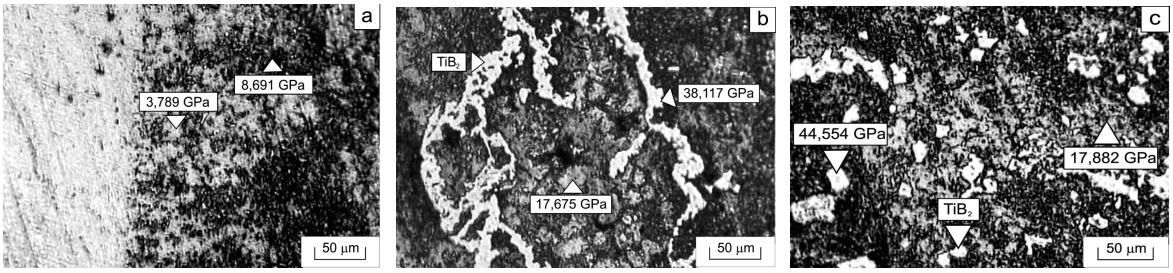


Fig. 1. Microstructure of the coating produced of thermoreactive powder mixture FeB(50–125 μm) + FeTi(200–315 μm): *a* — interface with the substrate; *b* — middle of the deposited layer; *c* — subsurface coating area.

Since the electron beam surfacing is carried out in many passes, the deposition of next layers increases the substrate temperature, lifetime of the liquid metal bath formed on the surface of the underlying deposited layer and reduces the melt crystallization rate. After the crystallization the matrix structure of the composite coating is an alloyed solid solution with highly nonuniform concentration, fine and coarse iron and titanium borides as well as with numerous nonequilibrium boride-based eutectics. This structure leads to the formation of heterogeneous coatings.

Figure 1,c illustrates the microstructure of the FeB(50–125 μm)+FeTi(200–315 μm) coating surface with solitary titanium diboride crystals, which evidently entered the melt due to convective mass transfer from the underlying layer in the middle of the coating. There is a structure on the coating surface which consists of large titanium diboride crystals (7÷22 μm) and heterogeneous metal binder

with nonuniform hardness. The binder is chaotically hardened by fine-grained (≤1 μm) compounds of titanium borides of other stoichiometry (Fig. 1,c). This is confirmed by the data of X-ray phase analysis showing that, along with pronounced reflections from $TiB_2$ and α-Fe, phases TiB, $Ti_2B$ and $Ti_2B_5$ are registered.

3.2. Coatings of thermoreactive powder mixture FeB(200–315 μm)+FeTi(200–315 μm) (coating 2)

The microstructural analysis of coatings produced of a mixture of coarse-grained powders having the same granulometric composition (coating *2*) has also shown that the coating structure is heterogeneous across the thickness (Fig. 2).

This is probably due to the fact that, because of the large powder particles and high crystallization rate, the time period when the concentration of alloying elements in the formed melt becomes uniform was too short. The nonuniform melt crystallization resulted in the formation of specific structures at the interface with the substrate and in the middle of the deposited layer.

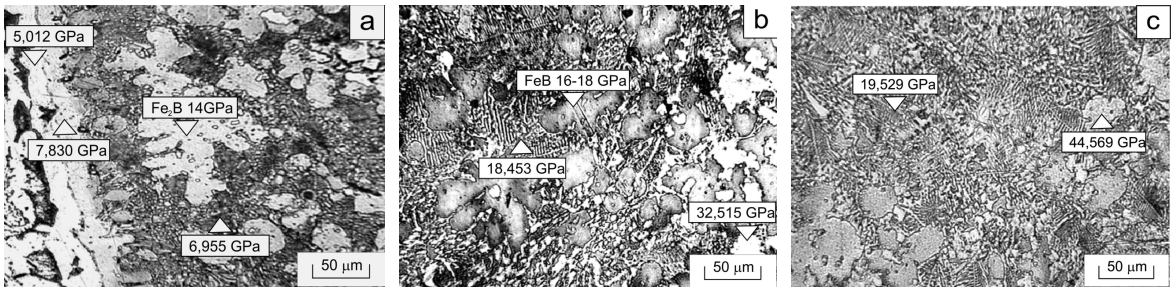


Fig. 2. Microstructure of the coating produced of thermoreactive powder mixture FeB(200–315 μm)+FeTi(200–315 μm): *a* — interface with the substrate; *b* —— middle of the deposited layer; *c* — subsurface coating zone.

The structures have irregularly shaped regions in the form of light unetched globules whose chemical composition differs across the coating thickness. By the data of X-ray spectrum microanalysis, the above solid solution regions at the interface have the composition of $Fe_2B$ and hardness $H \approx 14$ GPa (Fig. 2,a). In the middle of the coating (Fig. 2,c) the globules became three-dimensional and darker in color. These regions have the composition of FeB and hardness $H = 16–18$ GPa. The FeB formation is evidently caused by the fact that with distance from the coating – substrate interface and increasing number of passes the melt temperature grows and the degree of its saturation with boron also increases owing to a more complete dissolution of initial FeB powder particles.

Such melt crystallizes with the formation of regions in the coating structure which have the composition of FeB, being separated by fine-grained particles and their conglomerates whose hardness ($H = 32.5$ GPa) corresponds to the $TiB_2$ phase. One can also see from Figs. 2,b,c that the metal binder structure between the unetched regions exhibits heterogeneous phase morphology and nonuniform hardness ($H = 6–19$ GPa). It has numerous regions with dendritic and eutectic structure whose hardness reduces with the eutectic size refinement. According to the X-ray phase analysis, the eutectics can be the $Fe_2B$-Fe and $TiB_2$-Fe compounds [4, 5]. When surfacing powders of the given granulometric composition, we observed the highest fluidity of the formed melt as compared to coatings *1* and *3*.

3.3. Coatings of thermoreactive powder mixture FeB(200–315 μm)+FeTi(50–200 μm) (coating 3)

After coating deposition we had a layered structure, in which every layer mainly contained one phase component across its thickness (Figs. 3,a–c).

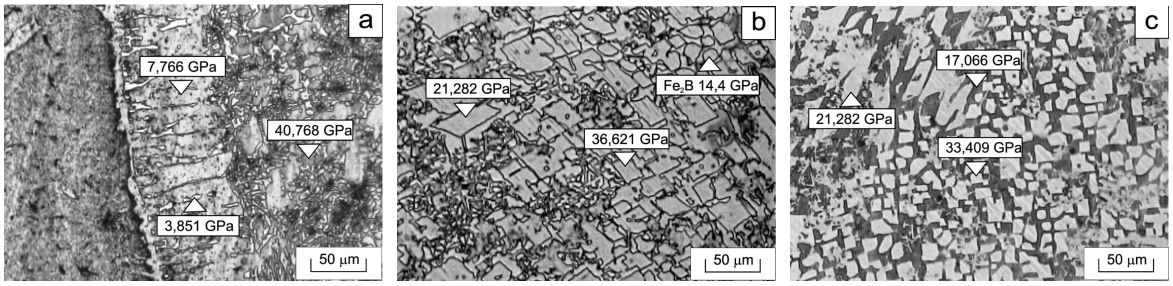


Fig. 3. Microstructure of the coating produced of thermoreactive powder mixture FeB(200–315 μm)+FeTi(50–200 μm): *a* — interface with the substrate; *b* —— middle of the deposited layer; *c* – – subsurface coating region.

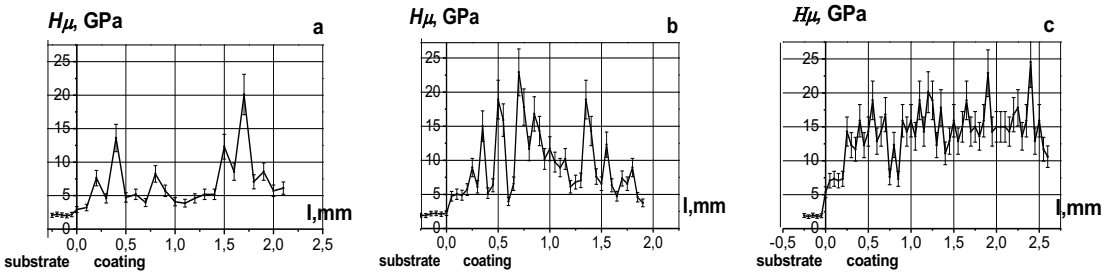


Fig. 4. Distribution of microhardness *H*μ in the coating: *a* — FeB(50–125 μm) + FeTi(200–315 μm); *b* — FeB(200–315 μm)+FeTi(200–315 μm); *c* — FeB(200–315 μm)+FeTi(50–200 μm).

In the middle of the coating at 1.3 mm from the interface with the substrate (Fig. 3,b) the structure mainly consists of rounded $Fe_2B$ particles of size 8–12 μm and hardness $H$ = 14.4 GPa, rectangular titanium diboride crystals (4–6 μm) and larger elongated titanium boride particles embedded in the $Fe_2B$-Fe eutectic matrix. The subsurface coating region (Fig. 3,c) also has heterogeneous phase composition: the left part of the microscan demonstrates aggregates of titanium borides, the right part — a microstructure region with uniform distribution of 10–17 μm light crystals in the metal binder which are titanium borides and diborides (TiB, $TiB_2$). The hardness of the particles is in the interval $H$ = 22–34 GPa.

3.4. Coatings of a mixture of thermoreactive FeB – FeTi powders with amorphous boron

In the literature [6] amorphous boron is referred to active admixtures. Even in small quantities (3÷6 mass %) it improves the structure of fused coatings owing to the formation of low-melting eutectics that accelerate the interaction of components with each other and at the interface with the substrate. Other papers show that boron admixtures are not surface-active, being the diffusion barrier for the dissolution of solid phase components in liquid alloys and impeding the formation of contact eutectics. With growing boron content, the angle of contact between titanium borides and Fe–B melts increases and the fluidity of formed melts reduces [7].

We study the influence of amorphous boron on the structure and properties of coatings produced by vacuum electron beam surfacing depending on its concentration in the fused powder (3 or 6 mass % $B_{am}$).

The comparative analysis of coating structures reveals that the introduction of 3 mass % of $B_{am}$ into the initial mixture causes the formation of finer structure, which is highly heterogeneous across the coating thickness and shows regions of very different phase morphology. This coating is characterized by a nonuniform distribution of the metal intergranular binding phase across the whole coating (Fig. 5). Of particular notice are the morphological features and phase composition of the near-interface region of the coating. Figure 5,a clearly demonstrates that the transition region structure, in contrast to earlier studied compositions, is highly saturated with brittle elongated particles of the $Fe_2B$ phase, as found in X-ray spectrum microanalysis. The particles and their aggregates are chaotically distributed in the iron matrix that mainly consists of regions free from precipitates and fine-grained interparticle binder, which is hypothetically the $Fe_2B$–Fe eutectic.

Figure 5,b illustrates a structure fragment in the middle of the deposited 3 mass % $B_{am}$ coating. There are two zones, one of which has a pronounced texture with elongated second-phase particles. By the X-ray spectrum microanalysis data, the largest particles of hardness $H\mu$ = 16.8–17.7 GPa are iron borides (FeB), and finer elongated particles of hardness $H\mu$ = 20–22 GPa are titanium borides (TiB). The second zone is free from large boride particles, showing fine spherical particles 1–3 μm in size uniformly distributed in the metal matrix. The microhardness of these particles is $H\mu$ = 14–16 GPa.

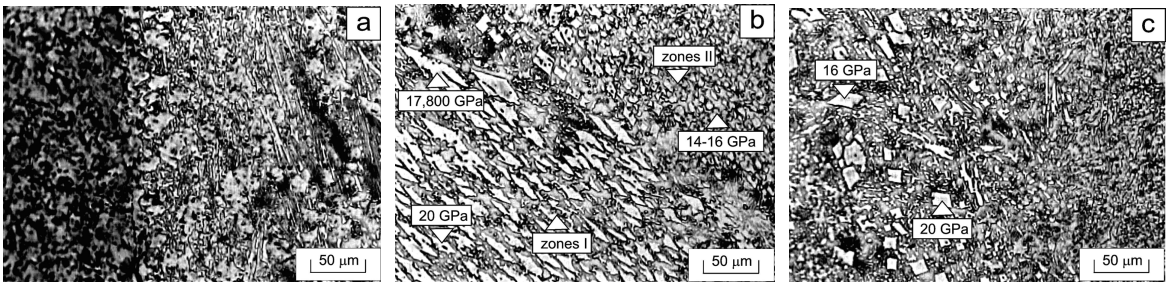


Fig. 5. Microstructure of coating FeB(200-315 μm) + FeTi(50–200 μm) + 3 % $B_{am}$: *a* — interface with the substrate; *b* — middle of the deposited coating; *c* — subsurface coating region

The microstructure of the 3 mass % $B_{am}$ coating surface has the same phase composition. Titanium and iron borides appear as single cut or needle-shaped particles nonuniformly distributed in the solid phase volume, and as structural components in the eutectic composition. As for the $TiB_2$ phase in the coating structure, it was revealed in X-ray phase analysis, but not in metallographic analysis, which is evidently due to the fact that titanium diborides are very fine and part of them are present in the composition of eutectics, e.g., $TiB_2$ – Fe.

By increasing the $B_{am}$ content in the fused mixture to 6 mass %, we obtained more homogeneous structures across the coating thickness, as evidenced by the uniform distribution of refractory particles in the metal binder and similarity of their average sizes in each layer. As seen from the microscans in Fig. 6, second-phase particles in the middle of the coating are surrounded by a thick layer of crystallized high-boron melt and they are rounded. This is testimony to active recrystallization of initial FeB and FeTi particles and products of their reaction (titanium borides) with the high-boron melt, which induces their average size growth through diffusion coalescence. The particle size in the middle of the coating is no more than 20 μm.

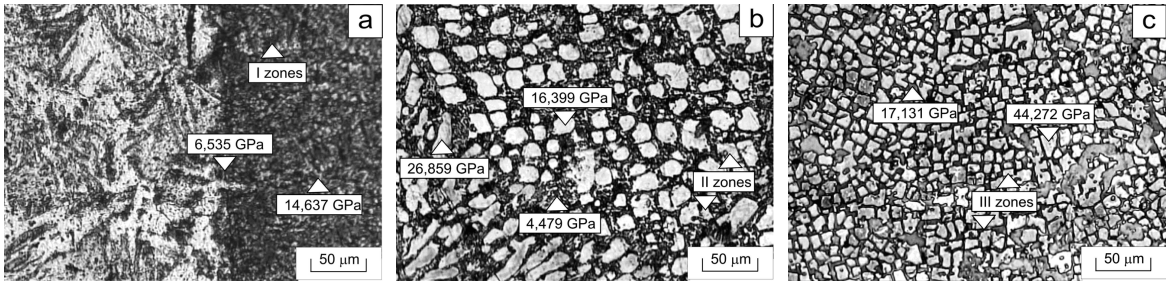


Fig. 6. Microstructure of coating FeB(200-315 μm) + FeTi(50–200 μm) + 6 % $B_{am}$: *a* — interface with the substrate; *b* — coating region at a distance of 0.5 μm from the interface with the substrate; *c* — subsurface coating region

Using X-ray structural analysis of the middle coating part as well as nanohardness values determined for individual phase components, we have defined their phase composition. The rounded particles of hardness $H$ = 16–18 GPa are iron borides (FeB), while elongated particles of irregularly oval shape 25–50 μm in the horizontal plane and hardness $H$ = 26–28 GPa are titanium borides (TiB). The surface microstructure mainly consists of cut titanium diboride particles not exceeding 12 μm in size and oval titanium boride particles uniformly distributed in the matrix saturated with fine particles. The X-ray spectrum microanalysis of the metal binder has revealed that its composition corresponds to the FeB compound present in the composition of the solid solution, which is observed between titanium boride particles both as extended layers and as coagulated rounded grains.

The dependences of the coating hardness on the amorphous boron content in the fused mixture are given in Fig. 7,a and 7,b. From comparative analysis, the average microhardness of the coatings prior to and after alloying with 3 mass % of $B_{am}$ actually remains the same.

At the same time, at the given amorphous boron concentration the microhardness greatly varies across the coating thickness in compliance with the heterogeneous structure formed at electron beam surfacing. Besides, as obvious from the microhardness distribution curves, with amorphous boron content growth to 6 mass % the average hardness of the deposited layer increases by about 5 GPa compared to the first two compositions. This results (i) from a higher alloying degree of the solid solution formed after the interaction and crystallization of the high-boron ferroboron and ferrotitanium melt, and (ii) from the formation of finer and harder high-boron phases, i.e., titanium borides and diborides, in the structure of the subsurface coating region.

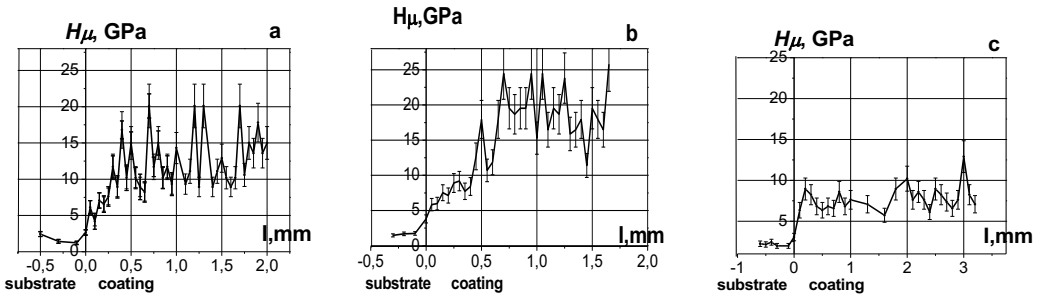


Fig. 7. Distribution of microhardness $H\mu$ in the deposited coatings: *a* — FeB(200-315 μm) + FeTi(50–200 μm) + 3 % $B_{am}$; *b* — FeB(200-315 μm) + FeTi(50–200 μm) + 6 % $B_{am}$; *c* — FeB(200-315 μm) + FeTi(50–200 μm) + 1 % $ZrO_2$

The metallographic study results indicate that the major differences in the structure of 3 and 6 mass % $B_{am}$ coatings are in the size and morphology of excess titanium and iron borides, and in the degree of solid solution hardening which increases with $B_{am}$ content growth in the fused mixture. Such structural rearrangement can greatly reduce the ductility of the deposited coatings.

We have also studied the structure of transverse fracture surfaces of the coatings and qualitatively estimated how strongly amorphous boron influences the coating fracture under shock loading. Figure 8 shows the transverse fracture in the subsurface regions of coatings produced of powder mixture FeB(200-315 μm) + FeTi(50–200 μm) and alloyed with 3 and 6 mass % of $B_{am}$. The comparison of the fracture patterns reveals that in the coating of initial composition the fracture is of mixed type: brittle fracture occurs along iron and titanium boride particles, and quasi-viscous fracture along the metal binder (Fig. 8,a).

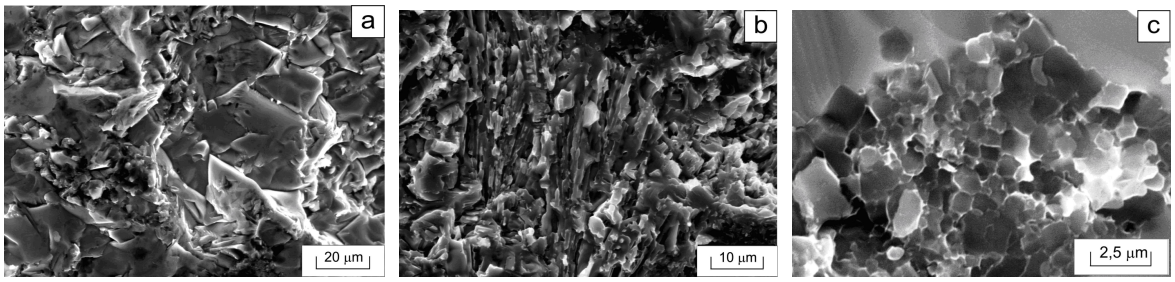


Fig. 8. Transverse fracture patterns in the subsurface coating regions: *a* — FeB(200–315 μm) + FeTi(50–200 μm); *b* — FeB(200–315 μm) + FeTi(50–160 μm) + 3 % $B_{am}$; *c* — FeB(200–315 μm) + FeTi(50–160 μm) + 6 % $B_{am}$

In the case of coatings made of the mixture with 3 and 6 mass % of $B_{am}$, the fracture is typically brittle: the fracture surfaces are zones of brittle intercrystalline and internal transcrystalline cleavage fracture of boride particles (Fig. 8,b), with higher fraction of brittle intercrystalline fracture and phase layering than in the 6 mass % $B_{am}$ coatings. The latter is evidently due to that the formed high-boron melt after its reaction with the ferrotitanium melt and crystallization favors primarily the formation of titanium diboride crystals in the coating structure. The metal binder is therewith dispersion hardened by fine (0.2–0.6 μm) titanium diboride particles precipitated from the solid solution. Figure 8,c illustrates a fragment of the metal binder microstructure in the interparticle space (between titanium diboride crystals). One can see the degree of the metal binder saturation with boride particles.

The size and concentration of titanium borides in the metal binder is maximum in the surface layer of the 6 mass % $B_{am}$ coating. This significantly reduces the intergranular fracture viscosity and causes cracking in local regions of the subsurface layer, or even generation of macrocracks propagating along phase boundaries and in the binder volume which leads to early brittle fracture of boride coatings.

3.5. Coating structure formation with ultrafine $ZrO_2$ powder added into initial mixture

As has been found earlier in [8], at electron beam surfacing of thermoreactive FeB – FeTi powder mixture with more than 5 mass % of $ZrO_2$ the melt fluidity greatly decreases, the melt is poorly mixed, and a heterogeneous coating structure with nonfused zones is formed after crystallization.

With 10 and 15 mass % of $ZrO_2$ added into the fused mixture, the obtained coating structures correspond to the solid phase sintering mode with high hardness and porosity. An example is given in

Fig. 9 that illustrates the microstructure and microhardness of the surface zone in the 15 mass % $ZrO_2$ coating.

At the same time, as was expected, alloying with zirconia leads to significant structure refinement of the coatings and increases their hardness and wear resistance.

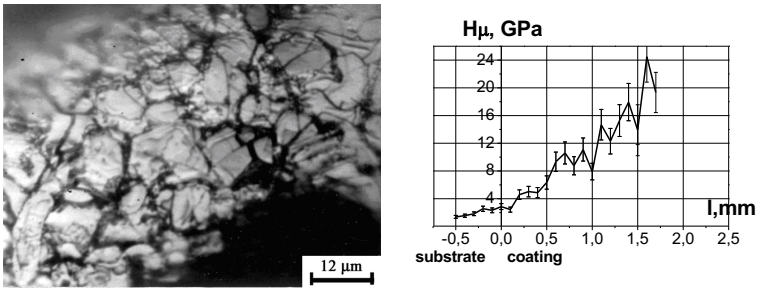


Fig. 9. Microstructure and microhardness of coating FeB(125–200 μm) + FeTi(150–200 μm) + 15 % $ZrO_2$

As a result, we looked for the efficient concentration of zirconia, which is a II type modifier, and studied its influence on the structure and hardness of the coating produced of thermoreactive powder mixture FeB(125–200 μm) + FeTi(50–200 μm) under the electron beam.

We have investigated coatings produced of a mixture of the above composition with 1 mass % of $ZrO_2$ added. Figure 10 gives the microstructure scans of such a coating made in different zones across its thickness.

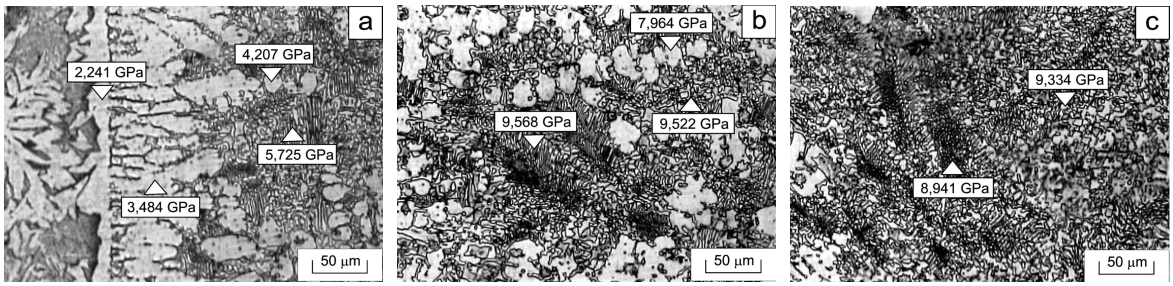


Fig. 10. Microstructure of coating FeB FeB(200–315 μm) + FeTi(50–200 μm) + 1 % $ZrO_2$: *a* — interface with the substrate; *b* — middle of the coating; *c* — subsurface coating region

According to the metallographic analysis data, the introduction of 1 mass % of $ZrO_2$ into the mixture modifies the coating structure. The size of its components is greatly refined compared to the coating of initial composition. The coating structure demonstrates aggregates of polyhedral and rounded titanium diboride and boride particles of size 1–13 μm and hardness 27–34 GPa. Since the formed coating structure is of eutectic type (Fig.10,c), fine-grained titanium and iron borides can be also present in the

composition of numerous eutectics on their basis: $Fe_2Ti$ – Fe, $Fe_2B$ – Fe, $TiB_2$ – Fe. In this case, the deposited layer has uniform hardness distribution across the thickness, though the maximum $H\mu$ values are two times lower than in 10–15 mass % $ZrO_2$ coatings: 12 GPa vs. 24 GPa.

Fractographic analysis has shown that at the "1 mass % $ZrO_2$ coating – substrate" interface, where the structure mainly consists of columnar α-solid solution dendrites perpendicular to the coating surface, there occurs viscous microfracture through the nucleation and coalescence of microvoids, which is testimony to high plastic deformation in the interface region (Fig. 11,a).

With growing alloying degree of the crystallized melt, the intergranular fracture viscosity greatly decreases in the middle and subsurface coating region, because liquid phase layers reduce in the interparticle space. Consequently, the surface coating layers undergo primarily brittle intercrystalline fracture.

As evident from the above findings, in order to obtain a high-quality coating with homogeneous fine-grained structure of thermoreactive powder mixture and retain its properties, the $ZrO_2$ concentration must not exceed 1 mass %.

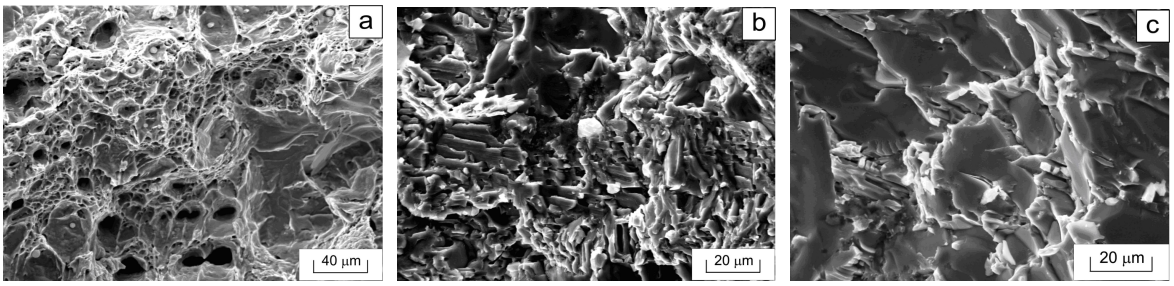


Fig. 11. Fracture surfaces of coating FeB(200–315 μm) + FeTi(50–200 μm) + 1 % $ZrO_2$: *a* — region near the substrate; *b* — middle of the coating; *c* — subsurface coating region

To find whether titanium borides can be used as the solid phase, we studied its abrasive and structural wear resistance in dry sliding friction and lubricated friction. The wear resistance in both abrasive and friction wear is found to correlate with the aggregate hardness of the deposited Fe-B-Ti coatings and depend on the volume fraction of the refractory component in the surface region, phase morphology and degree of metal binder hardening (Table 2)

Friction coefficient (*f*), wear rate (*I*, μm/km), wear coefficient ($K_W$), and microhardness (GPa) of coatings produced by electron beam surfacing

Table 2

| Coating composition | Friction coefficient, $f_{wear}$ | | Wear rate, $I$, μm/km | | Coating surface hardness,GPa | $K_W$ |
|---|---|---|---|---|---|---|
| | 5 cm/s | 11 cm/s | 5 cm/s | 11 cm/s | | |
| FeB(50–125)+ FeTi(200–315) | min – 0.142<br>max – 0.702<br>aver. – 0.433 | min – 0.16<br>max – 0.618<br>aver. – 0.31 | 2.28 | 1.29 | 5–7 | 1.86 |
| FeB(200–315)+ FeTi(200–315) | min – 0.148<br>max – 0.803<br>aver. – 0.526 | min – 0.160<br>max – 0.633<br>aver. – 0.395 | 2.32 | 1.45 | 10–12 | 5.72 |
| FeB(200–315)+ FeTi(50–200) | min – 0.153<br>max – 0.632<br>aver. – 0.515 | min – 0.168<br>max – 0.594<br>aver. – 0.517 | 1.61 | 3.31 | 15–20 | 11.3 |
| FeB(200–315)+ FeTi(50–200) +3%$B_{am}$ | min – 0.028<br>max – 0.250<br>aver. – 0.20 | min – 0.137<br>max – 0.228<br>aver. –0.192 | - | - | 15-17 | 16.8 |
| FeB(200–315)+ FeTi(50–200) +6%$B_{am}$ | min – 0.138<br>max – 0.48<br>aver. –0.42 | min – 0.151<br>max – 0.752<br>aver. –0.479 | 2.39 | 6.34 | 20-25 | 21 |
| FeB(200–315)+ FeTi(50–200) +1%$ZrO_2$ | min – 0.109<br>max – 0.570<br>aver. –0.340 | min – 0.131<br>max – 0.446<br>aver. –0.310 | - | - | 8-12 | 19.4 |

## 4. CONCLUSIONS

The electron beam surfacing of thermoreactive Fe-B-Ti powders allows producing composite coatings on the basis of refractory titanium borides synthesized under the electron beam in vacuum. Such coatings exhibit high abrasive wear resistance and low wear rate in dry friction.

The granulometric composition of the fused powder mixtures strongly influences the physico-chemical processes occurring in the molten bath under the electron beam. It defines the coating properties that depend on the structure, proportion of boride phases and the metal binder, and the degree of solid solution hardening.

We have studied a dispersion hardening mode based on the introduction of ultrafine-grained powders — I and II type modifiers — into the fused mixture. It is found to be a good way of improving the heterogeneity of the system at the cost of composite coating formation with multilayer structure and increased mechanical characteristics.

In order to produce high-quality composite coatings by electron beam surfacing, the content of amorphous boron in the fused mixture must be no more than 3 mass %, and zicornia no more than 1 mass %.

The composite coatings produced of Fe-B-Ti system by electron beam surfacing can be applied as wear resistant materials.

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