Improving die tooling properties by spraying TiC-Ti-Al and TiB₂-Ti-Al electro-explosive coatings

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Abstract
This article describes increasing wear resistance of 5CrNiMo die steel by more than 5 times. This effect is achieved by creating TiC-Ti-Al and TiB₂-Ti-Al coatings on the surface of 5CrNiMo die steel. The microhardness of the formed coatings depends on which part of the structure is measured. The microhardness differs by more than 12 times in the matrix material and in the inclusions of titanium carbides and borides. However, the combination of metal matrix composites and the reinforcing inclusions suggests a high complex of properties of the formed coatings. The formation of wear-resistant coatings of these systems is carried out by two-stage treatment. At the first stage, electro-explosive spraying of TiC-Ti-Al or TiB₂-Ti-Al coatings is performed. At the second stage, electron-beam treatment of these coatings is carried out. The structure uniformity during electro-explosive spraying is enforced by specially designed composite conductors, which are electrically exploded. The reason for wear resistance increase is the formation of a multiphase finely dispersed structure in coatings based on TiC, Al₃Ti, Ti and Ti₃Al phases for TiC-Ti-Al system and TiB₂, TiB and AlTi₃ phases for TiB₂-Ti-Al system. The structure was also studied in detail at the interface between the coatings and the substrate using transmission electron microscopy. The studies of the structure of electro-explosive coatings were compared with the structural features of TiC-Ti-Al composite coatings obtained by the laser cladding technique on the surface of TiAl alloy. Comparison of the findings of the structure obtained by these two different spraying methods revealed both general patterns and characteristic features for each of the coating methods. They relate to features at the interface between the coatings and the substrate, as well as characteristic unitary coating layers.

Introduction
Die forming is carried out on special metalworking equipment—presses for various purposes [1]. Die tooling is a variety of elements, parts and devices that are used to give the body a certain shape and size [2]. Such tools allow the deformation of bodies from various materials [3]. Die tools are currently manufactured by world-famous companies, manufacturing machine tools for metal treatment and other industrial equipment [4], such as Boschert GmbH + Co KG, FIBRO GmbH, HBS Bolzenschweiss-Systeme GmbH & Co, Bolzenschweistechnik GmbH from Germany, Rolleri SpA, FAR Srl from Italy, Stierli Bieger AG from Switzerland, Heinz Soyer ARTAFAST snc from Spain and many others. Such tooling includes components for die forming and a wide range of various parts, which provide high-quality and fast forming of the necessary elements [5]. The above information confirms the global distribution of dies. Large, medium and small dies for die forming are currently represented by dies for separating operations (cutting, punching, trimming) [6]; dies for bending, flanging [7]; dies for forming operations (drawing, molding) [8]; dies of combined and sequential action [9]. High
temperature die tools undergo various loads [10] and the nature and intensity of these loads vary significantly in different parts of the working surface [11]. Today, repair of die tooling implies mostly restoration of the geometry lost in the process of operating the equipment with materials similar in composition to the tooling material [12]. In this case, increasing the equipment lifetime and productivity is not implied, and in most cases,
it is necessary to make a complete sampling of the previously deposited layer [13]. With a standard approach, the resource of equipment increases due to the use of expensive high-alloy materials [14]. World scientists suggest unique integrated technological solutions: the problem of repairing and extending the life time of one product can be solved by using a combination of materials with different characteristics, each solving its own problem [15]. First of all, this applies to equipment operating at high temperature loads in combination with high pressure and rapid temperature change [16]. Thus, the use of integrated treatment, including electro-explosive spraying of coatings of various systems [17] and subsequent electron-beam treatment allows for the achievement of high-grade surface properties [18]. The use of an integrated approach in the manufacture and repair of die tooling allows getting the maximum economic effect [19]. Extension of the life time of equipment is achieved by a multiple increase in tool life and results in decreasing maintenance downtime and increasing overhaul periods [20]. Subsequent repairs are carried out locally only in wear spots with a minimum sampling, which reduces the amount of necessary materials for subsequent repairs [21]. There is the effect of increasing the durability of equipment after each repair, which leads to an even greater economic effect [22]. A group of Indian scientists led by Veeresh Nayak C [23–25] are studying various materials obtained by injection molding, as well as sintered materials, by the microwave method. The aim of this work is the formation of TiC-Ti-Al and TiB2-Ti-Al coatings by electric-explosive spraying method and subsequent electron-beam treatment, as well as the study of their structure, phase composition, wear resistance, friction coefficient and microhardness.

Research materials and methods

Wear-resistant TiC-Ti-Al and TiB2-Ti-Al coatings were formed using die tooling from 5CrNiMo die steel. The die tooling area was 2.5 cm². 5CrNiMo steel was previously annealed to granular perlite. The coating was formed in two stages. First, electro-explosive spraying of TiC-Ti-Al and TiB2-Ti-Al coatings was carried out, followed by electron-beam treatment. Electro-explosive spraying was carried out with a composite electrically exploded conductor for coating (figure 1) and a modernized electro-explosive accelerator (figure 2). For TiC-Ti-Al the composite electrically exploded conductor (figure 1(a)) was a two-layer aluminum foil (570 mg) with titanium carbide and titanium powders enclosed in it (200 mg each). In case of TiB2-Ti-Al, the TiC powder of the
The composite electrically exploded conductor (figure 1b) was replaced by TiB$_2$ of the same mass (200 mg). The choice of identical masses of TiC and TiB$_2$ powders is due to the fact that their atomic mass is close to each other. The atomic mass of TiC is 59.867, and TiB$_2$ is 71.867 a.m.u. [26]. The absorbed power density during spraying was 4.5 GW m$^{-2}$, the diameter of the titanium nozzle was 20 mm, and the distance of the sample from the nozzle exit was 20 mm. Research was conducted on the EVU 60/10 laboratory electroexplosive unit in [27]. This equipment consists of a power source, a kilovoltmeter, a capacitor battery, controlled discharge unit, pulsed plasma accelerator, and discharge loop. The maximum energy reserve of the capacitive store is 60 kJ; the discharge current frequency is 10 kHz. Electron-beam treatment (EBT) of electro-explosive coatings was carried out in modes at a pulse time of 100 $\mu$s, the number of pulses 10 at a variable surface energy density of 45, 50, 55, and 60 J s$^{-2}$ (EBT modes No. 1, 2, 3, and 4, respectively) and at a pulse time of 200 $\mu$s, the number of pulses 20 and a surface energy density of 60 J s$^{-2}$ (EBT mode No. 5).

The resulted coatings were studied using scanning electron microscopy (Carl Zeiss EVO 50 XVP electron microscope with an attachment for X-ray energy dispersive analysis EDS X-Act), transmission electron microscopy (TEM) (FEI Tecnai 20 G2 TWIN electron microscopes) and X-ray diffraction analysis (ARLXTRA diffractometer). TEM foil was prepared using the Solartron Analytical 12558WB electrochemical system. The tribological parameters (coefficient of friction and wear resistance) of the coatings were investigated with the geometry of a disk pin on a CSEM tribometer (Switzerland) at room temperature and humidity. A diamond pyramid was used as a counterbody with track diameter 3.9 mm, rotation speed 1.5 cm / s, load 8 N, distance to stop 12.3 m for uncoated steel and 123 m for coated steel, number revolutions - 1000 for uncoated steel and 10000 for coated steel. The wear of the surface layer was determined after profilometry of the resulting track using a MicroMeasure 3D Station laser optical profilometer (Stil, France). Microhardness was measured using HVS-1000A microhardness meter.

**Figure 4.** The surface structure of high current pulsed electron beam treatment of electro-explosive coatings. (a), (b)–TiC-Ti-Al coatings; (c),(e)–TiB$_2$-Ti-Al coatings.
Figure 5. Characteristic cross-sectional structure of 5CrNiMo steel sample subjected to electro-explosive coating of TiC-Ti-Al after electron-beam treatment. Scanning electron microscopy. The dashed line on (a) shows the boundary between the coating and the substrate. The arrows on (e) show the dynamic rotation areas: (a) — cross section with overlapping distribution lines of chemical elements; (b) — the distribution of iron, titanium, aluminum and carbon in the coating along A-A line is marked in purple, blue, green and red, respectively; (c) — cross section; (d) — features at the boundary of the coating and the substrate; (e) — dynamic rotation area; (f) — electro-explosive coating without electron-beam treatment; (g) — coating layer remelted during electron-beam treatment.
Research results and discussion

As the maximum loads are focused on die tooling during die forming, it should have high wear resistance. Therefore, at first the wear resistance of sprayed coatings was tested. TiC-Ti-Al and TiB2-Ti-Al coatings treated in EBT mode 3 had the best wear resistance characteristics. The measurement results of the wear rate W and the average value of the friction coefficient \( \mu \) of coatings showed that both characteristics of the coatings substantially depend on their elemental composition (table 1). An increase in the wear rate correlates with an increase in the average value of the friction coefficient: the higher the friction coefficient, the more intense the material wear (figure 3). 5CrNiMo steel showed the maximum wear rate among the test samples. TiC-Ti-Al and TiB2-Ti-Al coatings show an increase in wear resistance compared to 5CrNiMo steel by 5.4 and 5.0 times, respectively (table 1). This is to be expected. The change in wear resistance and friction coefficient is usually associated with a change in hardness [28]. In their turn, all of the above strength characteristics of the material...
### Table 2. X-ray analysis data of TiC-TiAl coatings.

| Mode electron-beam treatment | Detected phases | Percentage of phases, mass% | Crystal lattice parameters, Å | The size of the coherent scattering regions, nm | $\Delta d/d' \times 10^{-4}$ |
|------------------------------|-----------------|-----------------------------|-------------------------------|-----------------------------------------------|-----------------------------|
| 1                            | TiC             | 43.8                        | 4.2712                        | 79.16                                         | 12.65                       |
|                              | Al/Ti           | 42.8                        | a = 3.7755                    | 17.86                                         | 34.86                       |
|                              |                 |                             | c = 8.4527                    |                                               |                             |
|                              | Ti              | 13.0                        | 3.1403                        | 9.69                                          | 50.48                       |
|                              | Ti3Al           | 0.4                         | 3.5268                        | 31.23                                         | 37.9                        |
| 2                            | TiC             | 33.7                        | 4.2914                        | 46.36                                         | 19.05                       |
|                              | Al/Ti           | 26.1                        | a = 3.6942                    | 9.87                                          | 75.00                       |
|                              |                 |                             | c = 8.4100                    |                                               |                             |
|                              | Ti              | 5.9                         | 3.5535                        | 38.25                                         | 44.70                       |
|                              | Ti3Al           | 34.3                        | 4.0657                        | 10.06                                         | 70.36                       |
| 3                            | TiC             | 63.5                        | 4.2948                        | 46.94                                         | 8.03                        |
|                              | Al/Ti           | 18.8                        | a = 3.7388                    | 14.91                                         | 11.59                       |
|                              |                 |                             | c = 8.5117                    |                                               |                             |
|                              | Ti              | 17.4                        | 3.1639                        | 41.81                                         | 89.3                        |
|                              | Ti3Al           | 0.3                         | 3.6301                        | 8.32                                          | 56.84                       |
| 4                            | TiC             | 32.4                        | 4.2984                        | 36.0                                          | 69.33                       |
|                              | Al/Ti           | 43.7                        | a = 2.4368                    | 20.11                                         | 25.07                       |
|                              |                 |                             | c = 16.400                    |                                               |                             |
|                              | Ti              | 17.0                        | 3.1339                        | 20.26                                         | 69.33                       |
|                              | Ti3Al           | 6.9                         | 4.1127                        | 86.63                                         | 51.57                       |
| 5                            | TiC             | 45.04                       | 4.2952                        | 416.54                                        | 6.75                        |
|                              | Al/Ti           | 1.2                         | a = 3.7265                    | 19.87                                         | 43.45                       |
|                              |                 |                             | c = 8.4842                    |                                               |                             |
|                              | Ti              | 0.3                         | 3.5105                        | 17.79                                         | 15.58                       |
|                              | Ti3Al           | 53.46                       | 4.2043                        | 17.1                                          | 3.95                        |

### Table 3. X-ray analysis data of TiB$_2$-TiAl coatings.

| Mode electron-beam treatment | Detected phases | Percentage of phases, mass% | Crystal lattice parameters, Å | The size of the coherent scattering regions, nm | $\Delta d/d' \times 10^{-4}$ |
|------------------------------|-----------------|-----------------------------|-------------------------------|-----------------------------------------------|-----------------------------|
| 1                            | TiB$_2$         | 42.5                        | a = 3.0233                    | 29.18                                         | 13.54                       |
|                              | TiB             | 1.9                         | 4.2526                        | 28.02                                         | 12.12                       |
|                              | AlTi$_3$        | 55.6                        | a = 5.8177                    | 36.17                                         | 13.57                       |
|                              |                 |                             | c = 4.7007                    |                                               |                             |
| 2                            | TiB$_2$         | 28.5                        | a = 3.0286                    | 37.48                                         | 12.28                       |
|                              | TiB             | 17.2                        | 4.2601                        | 21.11                                         | 17.50                       |
|                              | AlTi$_3$        | 54.3                        | a = 5.7877                    | 36.17                                         | 13.57                       |
|                              |                 |                             | c = 4.6507                    |                                               |                             |
| 3                            | TiB$_2$         | 30.2                        | a = 3.0278                    | 28.02                                         | 13.51                       |
|                              | TiB             | 7.1                         | 4.2641                        | 56.31                                         | 25.53                       |
|                              | Ti3Al           | 42.7                        | a = 5.7359                    | 10.32                                         | 47.24                       |
|                              |                 |                             | c = 4.7183                    |                                               |                             |
| 4                            | TiB$_2$         | 28.5                        | a = 3.0284                    | 36.75                                         | 12.2                        |
|                              | TiB             | 17.2                        | 4.2602                        | 22.52                                         | 17.32                       |
|                              | AlTi$_3$        | 54.3                        | a = 5.7872                    | 38.12                                         | 13.47                       |
|                              |                 |                             | c = 4.6509                    |                                               |                             |
| 5                            | TiB$_2$         | 43.9                        | a = 3.0296                    | 32.61                                         | 10.86                       |
|                              | TiB             | 8.5                         | 4.2741                        | 25.06                                         | 24.84                       |
|                              | Ti3Al           | 47.6                        | a = 5.7507                    | 44.92                                         | 9.02                        |
|                              |                 |                             | c = 4.6271                    |                                               |                             |
are due to the state of its structure and elemental composition. The microhardness of TiC-Ti-Al coatings at the inclusions of titanium carbide is $2,400 \, HV$ and $200 \, HV$ in the matrix material. The microhardness of TiB$_2$-Ti-Al coatings is $2,500 \, HV$ at the inclusions of titanium diboride and $200 \, HV$ in the matrix material.

The treatment of die tooling made of 5CrNiMo die steel with TiC-Ti-Al and TiB$_2$-Ti-Al electro-explosive coatings sprayed onto its surface by an electron beam (in the indicated range of parameters) leads to essential transformations of both the surface of the sample and the surface layer (figure 4). In the central part of the zone, influenced by the electron beam (the area whose diameter increases from 10 mm at an energy density of the electron beam of $45 \, J \, cm^{-2}$ to 20 mm at $60 \, J \, cm^{-2}$), the characteristic structural components of the coating surface after electro-explosive coating, i.e. microdrops, flows and microcraters, disappear. The number of microcracks is reduced, the surface relief gets smoothed. At the same time, the emerging structure of the surface layer is very heterogeneous.

The volume ratio of the metal component (aluminum and titanium) and the particles of titanium carbide powder (for TiC-Ti-Al) or titanium diboride (for TiB$_2$-TiAl) in composite coatings correspond to their ratio in the composite electrically exploded conductor used for spraying. After electron-beam treatment of
Electro-explosive composite coatings, three characteristic morphological constituent structures, making microrelief of the coatings are formed on the surface: relatively smooth areas formed by high-speed crystallization cells with a cell size of 200 to 500 nm; areas containing titanium carbide particles (for TiC-Ti-Al) or titanium diboride particles (for TiB$_2$-Ti-Al); areas formed by spherical or plate-shaped titanium carbide particles (for TiC-Ti-Al) or titanium diboride particles (for TiB$_2$-TiAl), located in a metal matrix, formed by aluminum and titanium (figure 4). The cross-sectional structure of the coatings is pore-free Al–Ti matrix (figures 5, 6) with inclusions of titanium carbide (for TiC-Ti-Al) or titanium diboride (for TiB$_2$-TiAl), the sizes of which vary within from 0.5 to 2.5 μm. Titanium carbide or titanium diboride and the metal component (aluminum + titanium) are approximately equally distributed in the coating. For TiC-Ti-Al the formation of dynamic rotations is locally revealed [29] (figures 5(d), (e)). During the electron-beam treatment of

Figure 8. Electron microscopic image of the structure at the boundary of TiC-Ti-Al coating and 5CrNiMo steel substrate. Indication of micro electron diffraction patterns made it possible to identify reflections of titanium carbide (TiC) and α-Fe solid solution. (a)—bright-field image; (b)—micro electron diffraction pattern

Figure 9. Electron microscopic image of the structure at the boundary of TiC-Ti-Al coating and 5CrNiMo steel substrate. The arrow indicates the reflection in which a dark-field image is obtained for image b. (a)—bright-field image; (b)—dark-field image in γ-Fe reflection [220]; (c)—micro electron diffraction pattern
electro-explosive coatings, recrystallization of titanium carbide and titanium diboride occurs with the formation of other compounds. The study results of the structure of electro-explosive coatings are compatible with the data of the authors of the study [30] in which TiC-Ti-Al composite coatings were obtained by the laser cladding technique on the surface of TiAl alloy. The study stated that the growth direction of TiC dendrites depends on the size of the initial TiC powder. At micrometer size of TiC, the growth direction of dendrites is disordered, while at nanometer size of TiC, the morphology of the reinforcing phase of TiC is thin rods that are uniform at coating, in which case their growth direction is regular. As in the present study (figures 5, 6), the authors [30] obtained a composite coating structure, which was divided into four zones: a coating zone, a diffusion zone, a heat-affected zone, and a substrate. As applied to TiC-Ti-Al (figure 5) and TiB₂-Ti-Al (figure 6) electro-explosive coatings, there is no diffusion zone. This is due to the peculiarities of electro-explosive coating, such as shock wave action on the substrate and high-speed crystallization of the coating. Under such conditions, diffusion does not have time to develop. In TiC-Ti-Al, there is a heat affected zone 10–11 μm thick (figure 5(c)), but there is no such zone in TiB₂-Ti-Al. However, in TiB₂-Ti-Al, distinctive features arise at the interface between the coating and the substrate (figure 6(c)). Both TiC-Ti-Al coatings obtained by the laser cladding technique and electro-explosive coatings obtained in this work are non-porous dense coatings.

Figure 10. Structure at the boundary of TiB₂-Ti-Al coating with 5CrNiMo steel substrate. Transmission electron microscopy.
The data of X-ray diffraction analysis of TiC-Ti-Al and TiB$_2$-Ti-Al coatings are shown in tables 2 and 3. They coincide with the above results of the structure study obtained by scanning electron microscopy. The phase composite of TiC-Ti-Al coatings is represented by TiC, Al$_3$Ti, Ti, and Ti$_3$Al phases (table 2). The phase composite of TiB$_2$-Ti-Al coatings is represented by TiB$_2$, TiB, and AlTi$_3$ phases (table 3). The percentage of
phases, their lattice parameters and coherent scattering areas change depending on the electron-beam mode. Such changes are due to the interaction of the electron beam with the irradiated sample [31].

Electron microscopic micro diffraction studies of thin foils showed that TiC-Ti-Al coating structure deposited on 5CrNiMo steel and further treated with an intense pulsed electron beam at the interface with the substrate is multiphase and contains titanium carbide of TiC composite, a solid solution based on \(\alpha\)-iron (a body-centered cubic lattice) and a solid solution based on \(\gamma\)-Fe (austenite, a face-centered cubic lattice). Titanium carbide particles have a globular shape (figure 7); the average particle sizes of titanium carbide vary between 100–130 nm (figure 7). The \(\alpha\)-phase and \(\gamma\)-phase also have a globular shape. The dimensions of the \(\alpha\)-phase and the \(\gamma\)-phase are significantly larger, relative to the particles of the carbide phase, and vary within 0.8–1.0 \(\mu m\) (figures 8, 9).

The structure at the boundary of TiB\(_2\)-Ti-Al coating and the substrate is formed by plate-shaped inclusions whose transverse dimensions vary between 0.7–1.0 \(\mu m\); longitudinal dimensions vary from 0.7 to 3.5 microns (figure 10). Lamellar inclusions are adjacent to rounded (globular) inclusions, the sizes of which vary over a very wide range from 50 nm to 200 nm. The \(\alpha\)-phase grains shown in figure 11 are an iron-based solid solution with a body-centered cubic lattice; grain size is from 0.5 \(\mu m\) to 1.5 \(\mu m\). Ti\(_{3.3}\)Al inclusions are located along the grain boundaries of the \(\alpha\)-phase (\(\alpha\)-Fe plane reflections [135] are highlighted in color); particle sizes vary from 30 nm to 50 nm. The shape of the \(\alpha\)-phase is characterized by figure 12. At the boundaries of the \(\alpha\)-phase plates, iron boride precipitates of Fe\(_3\)B composite are located. Particles have the form of interlayers. The particle sizes of Fe\(_3\)B vary in the range of 30–50 nm. Figure 13 shows images of Fe\(_2\)Ti particles located at the grain boundaries of the \(\alpha\)-phase. Particle sizes vary between 30–40 nm. Lamellar inclusions are titanium aluminides of Al\(_3\)Ti composition (figure 14). Along with lamellar inclusions, polygon-shaped inclusions are present at the boundary of TiB\(_2\)-Ti-Al coating and the substrate (figure 15). The micro-electron diffraction analysis shows that such inclusions are aluminum borides of AlB\(_{12}\) composite. Thus, studies performed by diffraction electron microscopy revealed the formation of a multiphase structure at the boundary of TiB\(_2\)-Ti-Al coating and the substrate. The phase sizes of this structure vary from tens of nanometers to units of micrometers. The phase composition of the surface layer, revealed by micro-electron diffraction, is represented by the following phases: \(\alpha\)-phase (solid solution based on the BCC lattice), titanium aluminide Al\(_3\)Ti and Ti\(_{3.3}\)Al, boron aluminide AlB\(_{12}\), iron boride Fe\(_3\)B, titanium ferrite Fe\(_5\)Ti.

Figure 13. Electron microscopic image of the structure at the boundary of TiB\(_2\)-Ti-Al coating and 5CrNiMo steel substrate; (a)—bright-field image; (b)—dark-field image in [011]\(\alpha\)-Fe + [110]Fe\(_2\)Ti reflection; (c)—micro electron diffraction pattern (the arrow indicates reflections in which a dark-field image is obtained). The arrows indicate Fe\(_3\)Ti particles.
Conclusion

Wear-resistant TiC-Ti-Al and TiB<sub>2</sub>-Ti-Al coatings on 5CrNiMo steel of die tooling were obtained for the first time by electro-explosive spraying method and subsequent electron-beam treatment. Wear resistance of the obtained TiC-Ti-Al and TiB<sub>2</sub>-Ti-Al coatings is 5.4 and 5.0 times higher compared to 5CrNiMo steel. The microhardness of TiC-Ti-Al coatings at the inclusions of titanium carbide is 2,400 HV and 200 HV in the matrix material. The microhardness of TiB<sub>2</sub>-Ti-Al coatings is 2,500 HV at the inclusions of titanium diboride and 200 HV in the matrix material.

The reason for the increase in wear resistance is the formation of a multiphase finely dispersed structure. For TiC-Ti-Al coatings, the phase composition is formed by TiC, Al<sub>2</sub>Ti, Ti, and Ti<sub>3</sub>Al phases and for TiB<sub>2</sub>-Ti-Al coatings it is formed by TiB<sub>2</sub>, TiB, and AlTi<sub>3</sub> phases. At the boundary of the coating and the substrate, a multiphase structure is formed with phase sizes varying from tens of nanometers to units of micrometers. The boundary of TiC-Ti-Al coating and the substrate is formed by titanium carbide of the globular TiC composition, α-phase and γ-Fe-based solid solution. The boundary of TiB<sub>2</sub>-Ti-Al coating and the substrate is formed by the α-phase, titanium aluminides Al<sub>3</sub>Ti and Ti<sub>3.3</sub>Al, boron aluminide AlB<sub>12</sub>, iron boride Fe<sub>3</sub>B, titanium ferrite Fe<sub>2</sub>Ti. The boundary of TiB<sub>2</sub>-Ti-Al coating and the substrate is formed by the α-phase, titanium aluminides Al<sub>3</sub>Ti and Ti<sub>3.3</sub>Al, boron aluminide AlB<sub>12</sub>, iron boride Fe<sub>3</sub>B, titanium ferrite Fe<sub>2</sub>Ti.
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Figure 15. Electron microscopic image of the structure at the boundary of TiB2-Ti-Al coating and 5CrNiMo steel substrate. The arrow indicates the reflection in which a dark-field image is obtained. (a)—bright-field image; (b)—dark-field image in [215]AlB12 reflection; (c)—micro electron diffraction pattern.
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