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The impact of deposition method on wear mechanisms of NiAl-15 wt.% CrB2 coatings

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Abstract

In this work, the effect of the deposition method on the wear mechanisms of NiAl–15% CrB_2 composite coatings was investigated. The wear rates of coatings produced by Plasma spraying, Detonation spraying and Electric-Spark Alloying (ESA) were evaluated using room-temperature "pin-on-disc" tribological tests. The worn surfaces and corresponding wear mechanisms were analyzed via SEM. The results demonstrate that incorporating CrB_2 into the NiAl matrix significantly enhances the wear resistance of the composite coatings, shifting the dominant wear mechanism from abrasive-adhesive to oxidative wear, regardless of the deposition technique.

Keywords: Plasma coatings, APS, Detonation coatings, D-gun, Electric-Spark Alloying coatings, ESA, intermetallic, NiAl, chromium diboride, CrB_2, friction, wear resistance

Statement of the problem (Introduction)

Due to its low density, high melting point, and excellent resistance to oxidation and corrosion, nickel aluminide (NiAl) is widely used in the aerospace industry as a protective coating for gas turbine engine components [1], [2], [3]. However, the application of NiAl as a high-temperature wear-resistant material is limited due to its thermal softening at temperatures above 500 °C [4], [5]. Under thermal and mechanical stress, high plastic deformation of the intermetallic compound leads to the destruction of protective Ni- and Al-based oxide films formed on its surface. The destroyed oxide films fail to prevent direct metal-to-metal contact of the friction pair components, triggering severe adhesive wear.

Analysis of recent research and publications (Literature review)

To improve wear resistance, intermetallic matrices are dispersion-reinforced with refractory compounds, which increase the strength and stiffness of the composite at elevated temperatures while acting as wear-resistant phases [6], [7], [8], [9], [10], [11], [12], [13], [14]. Based on previous studies of physicochemical interactions in NiAl–MeB_2 systems (where Me is Cr, Ti, or Zr), chromium diboride (CrB_2) was identified as a promising reinforcing phase [15]. Prior research has investigated the high-temperature friction behavior of NiAl–CrB_2 composite coatings deposited via Plasma, Detonation, and Electric-Spark methods. The introduction of chromium diboride was shown to enhance the strength and stiffness of the composite coating, preventing the degradation of surface oxide films on the intermetallic matrix and facilitating a transition to an oxidative wear mechanism [16], [17], [18], [19].

Highlighting previously unresolved parts of the general problem

Despite existing studies on the behavior of NiAl–CrB_2 coatings under high-temperature friction conditions, the specific wear mechanisms occurring under room-temperature testing, especially for Electric-Spark Alloyed coatings, remain insufficiently understood. During sliding contact, intense frictional heating leads to a significant localized temperature rise within the friction zone [20], [21], [22]. The dissipation of this heat is dictated by a range of factors, including coating morphology.

Coatings deposited by Plasma spraying, Detonation spraying, and Electric-Spark Alloying (ESA) exhibit fundamentally different microstructural characteristics (porosity, phase distribution, defect density, and interface boundary features) [16], [17], [19]. Consequently, these structural variations can result in substantial differences in their wear mechanisms.

Formulation of the purpose of the article (Purpose)

The purpose of this work is to investigate the effect of the coating deposition method on the wear mechanisms of NiAl-15% CrB_2 (wt. %) composite coatings under friction conditions at room temperature.

Methods

Commercial NiAl powders with a particle size of -40 μm and CrB_2 powders with a particle size of – 12 μm were used to deposit the coatings. NiAl coatings were obtained from the as-received powder, whereas composite powder materials for deposition of NiAl–15% CrB_2 coatings were manufactured by mixing intermetallic and boride powders in the required proportions, followed by hot pressing at 1300 °C. The sintered CPM briquettes were either crushed and classified to the required size for Plasma and Detonation spraying or cut to the required size for Electric-Spark Alloying. Further details on the deposition parameters of Ni and NiAl–15% CrB_2 coatings can be found in previous works [16], [17], [19].

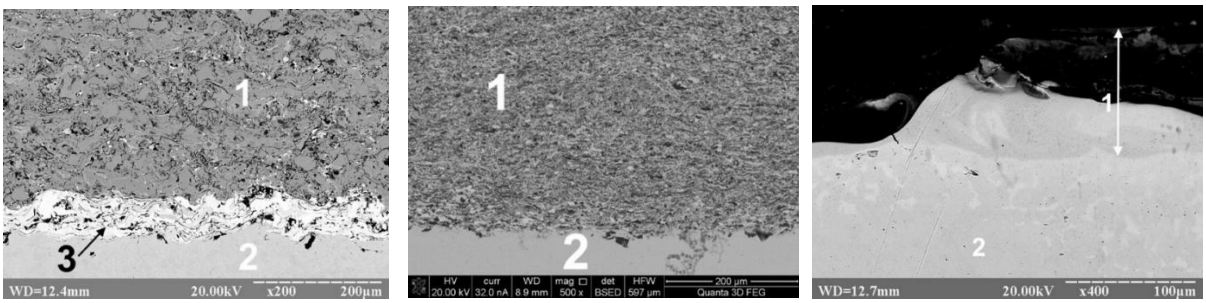

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Fig. 1. Microstructure of Plasma (a), Detonation (b) and ESA (c) coatings: 1 – coating; 2 – substrate; 3 – bond layer

To investigate wear resistance, the coatings were deposited onto steel pins (Ø 5 × 15 mm) made of Steel 20. In case of the Plasma spraying bond coating of Ni_3Al was used. The sprayed coatings were polished to a surface roughness of R_a = 2.5…0.63 μm.

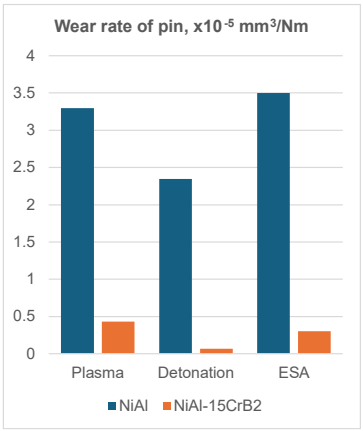

Fig. 2. Wear rate of NiAl–15% CrB_2 coatings (NiAl data provided for comparison)

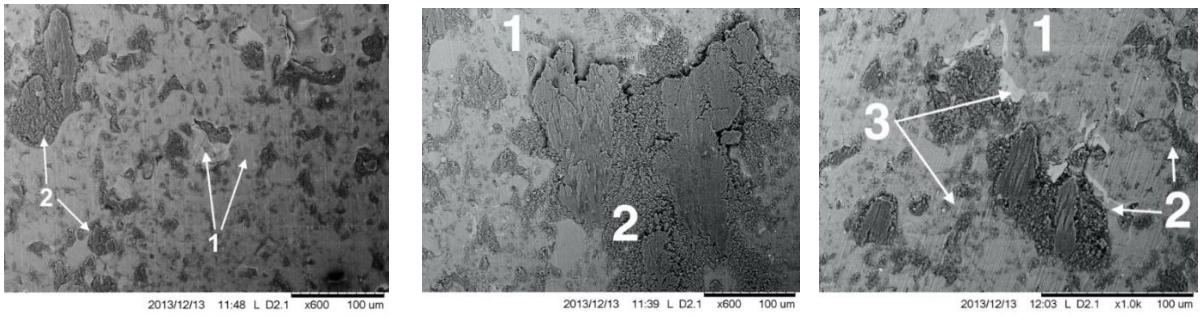

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Fig. 3. Worn surfaces of NiAl-15%CrB_2 Plasma coatings: 1 – coating, 2 – wear debris, 3 – wear tracks

The wear resistance of the coatings was determined by "pin-on-disc" scheme using a CETR UMT-2 micro-tribotester (Fig. 4). The pins were positioned at a distance *R*, pressed against the coating surface 4 with a specified force, and the disc holder 6 began to rotate at a programmed speed. The pins and counterbodies were mounted on the tribotester using custom-designed holders. Tribological testing was carried out at room temperature under the following conditions: S = 1.0 km, V = 0.157 m/s, P = 1 MPa.

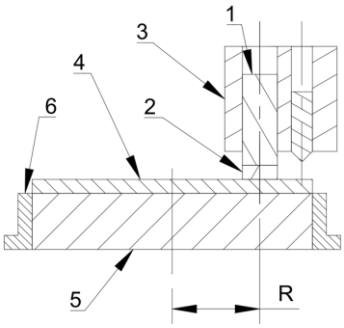

Fig. 4. Schematic of tribological testing: 1 – pin, 2 – NiAl-15% CrB_2 coating, 3 – pin holder, 4 – NiAl coating, 5 – disc, 6 – disc holder

To determine weight loss, the samples were cleaned before and after tribotesting in an ultrasonic bath filled with isopropyl alcohol (99.9%) and weighed on electronic scales with an accuracy of 0.0001 g. The determined weight loss of the coatings and the linear wear of the tribopair were converted to wear rate W_s using the following formula:

$$W_s = \frac{\Delta V}{P \cdot S} \tag{1}$$

where ΔV is the volume of worn material, mm^3; P is the normal load on the rod, N; S is the friction path, m.

Steel discs ∅ 40 × 10 mm (Fig. 4, 5) with a NiAl Plasma coating [17] (Fig. 4, 3) and a roughness of R_a = 2.5…0.63 μm were used as a counterbodies. Two tests were conducted on each disc. Initially, the pin was positioned at a distance R = 10 mm for the first test. After cleaning and taking all necessary measurements, disc 5 (Fig. 4) was reinserted into holder 6, and the holder with the new pin was positioned at a distance of R = 5 mm for the next test.

The composite coatings and worn surfaces were examined by scanning electron microscopy using REM-106I, Thermo Fisher Scientific Quanta 3D FEG, and Hitachi TM-1000 microscopes.

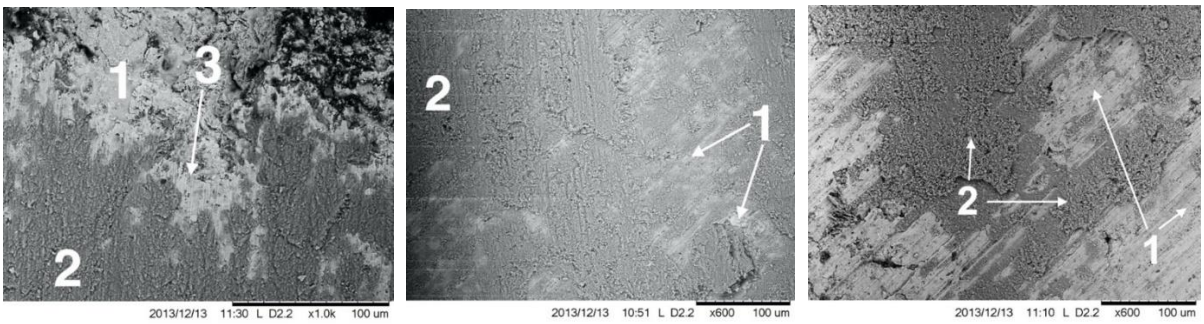

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Fig. 5. Worn surfaces of NiAl-15%CrB_2 Detonation coatings: 1 – coating, 2 – wear debris, 3 – wear tracks

Results

The microstructures of deposited coatings are shown in Fig. 1. Plasma and Detonation coatings exhibit a microstructure typical of thermally sprayed coatings: particles of CrB_2 evenly distributed in NiAl matrix. Detonation coating (Fig. 2, b) typically has noticeably smaller size of NiAl particles compared with Plasma coating (Fig. 1, a).

The different nature of the ESA method compared to thermal spraying results in a distinct microstructure. ESA coating is formed by an array of crystalized welding pools of different shapes and sizes (Fig. 1, c) without clear segregation of NiAl and CrB_2 particles. Additionally, it contains Steel 20 components, mainly Fe (around 10%). The coating is more than two times thinner than those produced by Plasma or Detonation spraying.

As expected, different microstructure of coatings resulted in difference of their wear behavior (Fig. 2). NiAl–15% CrB_2 Detonation coatings have the lowest wear rate. NiAl–15% CrB_2 Plasma and ESA coatings demonstrated similar wear rates, with the ESA coating performing slightly better. As expected, composite coatings

showed a wear rate ~7 times lower than NiAl ones which goes in line with the previous studies [16], [17], [18], [19]. It is worth noting that intense tribo-oxidation was observed during testing of the NiAl–15% CrB_2 Detonation coating. The surfaces of both the pin and disc were covered with pale-green films.

In order to investigate the nature of the processes that took place during the friction of NiAl–15% CrB_2 composite coatings, the worn surfaces were examined by SEM-EDX (Figs. 3–6). The worn surface of the plasma-sprayed coating is covered with conglomerates of wear debris (Fig. 3, point 2). The wear debris predominantly consists of Ni and Al oxides formed on the NiAl counterbody. Evidently, small volumes of the NiAl counterbody material in the contact zones were plasticized, leading to the shearing of oxide films and metallic NiAl fragments by the pin, which were then transformed into wear debris. During further sliding, this debris accumulated in surface defects of the composite coating (Fig. 3c, point 2). In some cases, either large individual defects or clusters of closely spaced defects trapped significant quantities of debris (Fig. 3b, point 2). These conglomerates of wear debris acted as a solid lubricant, thereby reducing the wear of the plasma-sprayed NiAl–15% CrB_2 coating. Evidently, a fraction of the wear debris not trapped by surface defects acted as an abrasive, leaving characteristic wear tracks on the NiAl matrix of the composite coating (Fig. 3c, 3).

The wear mechanism of the detonation coating is similar to that of the plasma-sprayed coating; however, in this case, the wear debris was predominantly trapped within surface grooves remaining from the polishing process (Fig. 5c, 2). On the leading edge (Fig. 5a), besides the wear debris (point 2) covering nearly the entire area, characteristic wear tracks (point 3) are also present. Intensive tribo-oxidation of the counterbody, followed by material transfer, resulted in almost the entire surface of the NiAl–15% CrB_2 detonation coating being covered with wear debris (Fig. 1b, 2). This debris acted as a solid lubricant, significantly reducing composite wear. Consequently, the NiAl–15% CrB_2 detonation coating exhibited the lowest wear rate.

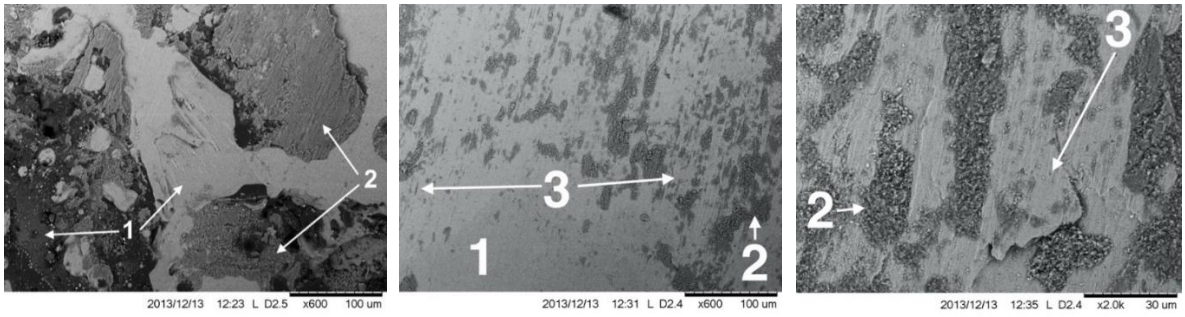

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Fig. 6. Worn surfaces of NiAl-15%CrB_2 ESA coatings: 1 – coating, 2 – wear debris, 3 – wear tracks

NiAl–15% CrB_2 Electric-Spark Alloyed (ESA) coatings exhibit a distinctly discrete surface topography, where variations in weld pool heights result in large depressions that accumulate wear debris (Fig. 6a, point 2). Additionally, regions with minor surface defects also trap wear debris (Fig. 6b and 6c, point 2). Furthermore, noticeable wear tracks and localized plastic deformation zones are observed within the ESA coating (Fig. 6a, point 1 and Fig. 6c, point 3). Evidently, owing to this discrete morphology, the normal load—and consequently the frictional heat—in certain contact zones is sufficiently high to induce plastic deformation of the NiAl matrix. However, this remains a localized phenomenon, as the majority of the coating surface is covered with wear debris acting as a solid lubricant.

Conclusions

In conclusion, the addition of CrB_2 into the NiAl matrix enhances its strength and suppresses noticeable plastic deformation, effectively shifting the primary wear mechanism from abrasive-adhesive (typical of the plain NiAl counterbody) to oxidative wear in the NiAl–15% CrB_2 Plasma, Detonation or ESA coatings. As a result, the wear rate of the composite coatings is ~7 times lower than that of the initial intermetallic ones.

NiAl–15% CrB_2 Detonation coating exhibited the highest wear resistance primarily due to the formation of a protective wear debris film covering nearly its entire surface. Despite differences in surface topologies and content both Plasma and Detonation composite coatings exhibited a similar level of wear resistance.

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Українець М.С., Уманський О.П., Полярус О.М.· , Коновал В.П., Левчук Т.О.· Вплив методу осадження на механізми зношування покриттів NiAl-15 мас.% CrB2

У цій роботі досліджено вплив методу нанесення на механізми зношування композиційних покриттів NiAl–15% CrB_2. Інтенсивність зношування покриттів, отриманих шляхом плазмового напилення, детонаційного напилення та електроіскрового легування (ЕІЛ), оцінювали за допомогою трибологічних випробувань за схемою «стрижень–диск» за кімнатної температури. Поверхні тертя та відповідні механізми зношування аналізували за допомогою растрової електронної мікроскопії (РЕМ). Результати демонструють, що введення CrB_2 у матрицю NiAl значно підвищує зносостійкість композиційних покриттів, змінюючи домінуючий механізм зношування з абразивно-адгезійного на окиснювальний, незалежно від технології нанесення.

Ключові слова: плазмові покриття, детонаційні покриття, електроіскрове легування, ЕІЛ, інтерметалід, NiAl, диборид хрому, CrB_2, тертя, зносостійкість