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# Journal of Composites and Compounds

## Electrodeposition of Nickel matrix composite coatings via various Boride particles: A review

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### ABSTRACT

Composite electrodeposition or Electroplating is a process primarily applied in the industry through which metal substrates are coated with an additional phase, such as low-thickness films of a range of metals. Lately, the advent of coating based on metal matrix through deposition has been vital because the superior hardness has more improved wear and corrosion resistance than alloy-based or pure coatings of metal. Nickel is an engineering material, which has been broadly utilized for metal matrix applications. This paper summarizes recent research on the electrodeposition of nickel matrix composite coatings with borides ceramic particles. Some of these particles are  $ZrB_2$ ,  $BN$ ,  $TiB_2$ ,  $Ni_3B$ ,  $CrB_2$ , etc. in the nickel matrix. In addition, the most important results achieved in the field of these composite coatings were collected in this review.

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Peer review under responsibility of JCC Research Group

### ARTICLE INFORMATION

#### Article history:

Received 28 February 2021

Received in revised form 04 April 2021

Accepted 11 May 2021

#### Keywords:

Electroplating

Composite coatings

Nickel matrix

Borides

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### 1. Introduction

Metal matrix composite coatings produced via deposit have become more significant in latest years because of their high hardness, corrosion, and wear resistance than pristine metal or alloy coatings [1]. These characteristics are primarily determined by individual composition phases of a composite covering and, as a result, the distribution and quantity of co-deposited grains, which are influenced by several method variables, considering electrolyte composition, grains properties, and supplied

current [2-4]. Nickel is a widely used metal matrix because it is an engineering material. Because of their high anti-wear and hardness characteristics, nickel-matrix composites are gaining popularity for potential engineering applications [5-7].

In comparison to mechanical and thermal methods for preparing composite layers, such as metal spraying, powder metallurgy, and vacuum deposition, or nitriding, such as magnetron sputtering, electrodeposition offers a great and versatile path to the realization of detection coatings of composites (i.e., materials with far more than one phase) comprising particles distributed in a metal matrix [8-10]. The electroly-

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DOI: 10.1001.1.26765837.2021.3.7.4.9

<https://doi.org/10.52547/jcc.3.2.4>

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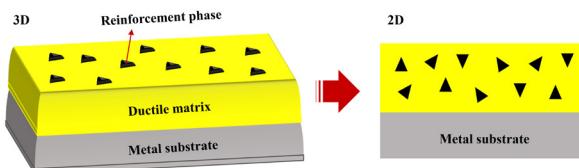


Fig. 1. The schematic of MMC coating on the metal substrate.

sis conditions (presence of additives, the content of the electrolyte bath, pH, electrolyte agitation, and temperature), current circumstances (the kind of enforced current and current density values), and the characteristic of the reinforcing grains (size, concentration, surface characteristics, and the type of distribution in the bath) are all factors that can affect the electrodeposition process and, therefore, the microstructure of the composite coating [11-13].

Composite electrodeposition is the process of incorporating second-step grains into the metallic composition during the electrodeposition process. Solid lubricants (graphite, PTFE,  $\text{BaF}_2$ ,  $\text{MoS}_2$ ), nitrides (AIN, TiN,  $\text{Si}_3\text{N}_4$ , and BN), carbides ( $\text{B}_4\text{C}$  and SiC), nanowires, flakes, whiskers, nanorods, nanotubes, and diamond are some of these particles [14-16]. The inclusion of small particles as the second step increases the surface hardness, corrosion resistance, wear resistance, and rising temperature inertness of composite coatings [17]. These characteristics are primarily determined by each matrix phase of a composite coating, as well as the quantity and dispersion of co-deposited grains, which are controlled by some process factors including particle properties, electrolyte composition, and supplied current [18, 19].

Composite plating was originally recorded in the United States in 1928 in a research of a Cu-graphite covering for such an automotive bearing [20]. The topic saw significant advancements in the 1960s and 1970s, especially in Europe, due to fondness in the diversity of probable coatings, the search for wear-resistant coatings, and the mechanism of particle co-deposition appropriate for rising automotive and aerospace engineering. Strong ceramic grains in beneficial engineering metal composites to realize Co or Ni layers containing, nitrides, or borides, carbides, such as WC or SiC, have received a lot of attention in the literature during this time [21].

Electrodeposited  $\text{Ni}_3\text{B}$  coatings are a relatively new research topic that has received a lot of attention in recent years [22, 23]. Ni- $\text{Ni}_3\text{B}$  coatings are used successfully in a variety of industries, including automotive, chemical, and electronics [24]. The  $\text{TiB}_2$  is a good anti-corrosive material and has excellent wear resistance and mechanical properties. Electrodeposition approaches have only been used in a few studies to incorporate  $\text{TiB}_2$  particles into the nickel matrix. Because of their extreme melting point, high hardness, chemical inertness, and oxidation resistance, coatings are based on Ni- $\text{TiB}_2$ . The research expressed that electrodeposition of nickel matrix composite coatings via boride particles showed improved properties compared to other coatings [25, 26].

In this study, we review principles of composite plating, nickel matrix composite coatings, and electrodeposition of these coatings via boride particles such as  $\text{Ni}_3\text{B}$ ,  $\text{ZrB}_2$ ,  $\text{CrB}_2$ , BN, and  $\text{TiB}_2$ . The results obtained from the publications can help to select the promotional materials in various industries.

## 2. Nickel matrix composite coatings

Metal matrix composite (MMC) is extensively used for strengthening engineering and substrate repair metal components as it combines

the high strength and hardness of the ceramic phase with the good hardness of the matrix. MMCs can be made of a variety of materials, including Be, Ti, Mg, Fe, Ni, Al, and Co [27-29]. The Ni-based MMC covering, which is discussed in the next section, is one of the most interesting and challenging metal matrices covering. Figure 1 shows the schematic of MMC coating on the metal substrate.

Nickel and its alloys have several advantages over other alloys, including corrosion resistance, wear resistance, and hardness. For this reason, industry and scientists are interested in using it in a composite coating matrix to improve magnetic properties, increase wear and corrosion resistance, and repair parts [30, 31]. Ni-based composite coatings have excellent high adhesive, and corrosion resistance, high bonding strength, and abrasive wear resistance making them useful in the industry [32-34]. Cutting tools, turbine blades, plungers and rollers, extruders, rolling mill rolls, rods, and piston heads, and wearing plates, for example, all benefit from Ni-based coatings. Vityaz et al. (1993) [35] published the first paper on Ni-based composite coating. They looked at the properties of a plasma coating of a tauboride-containing NiCrBTi alloy with 5-35 wt% TiC sprayed in the air, underwater, and vacuum. As a result, the Ni-based composite was further investigated, and many papers have been published on the subject.

In recent years, the electrodeposition of Ni coating has accounted for nearly 12% of global Ni consumption. The most common application of electroplated Ni coating is for decorative purposes [30]. Ni deposits are used in industry for a variety of purposes, including improving corrosion and wear resistance, changing the dimensions of small pieces, repairing eroded metals, improving magnetic properties, producing organic coatings, or preparing the substrate surface for glazing, and more [36]. An electrodeposition process can produce a Ni-based alloy and a Ni-based composite coating in addition to pure Ni coating. Sensor, electronic, optic industries, and communication all use this type of coating [37, 38].

## 3. The principles of the electrodeposition method for coating

Electrodeposition, also known as electroplating, is a method of depositing a coating on a substrate that is immersed in an electrolyte via electrolysis. This can be done in a high-temperature merged metal salt (melded salt electroplating) or in a room-temperature aqueous medium (aqueous solution electroplating). The major flaw of this method is its inability to achieve uniform thickness.

Aside from that, the important substrate surface preparation and the evaluation of hydrogen ions are its drawbacks [39-41]. Electroplating is commonly used for decorative coatings as well as low-level corrosion and wear resistance. Deposition of high-temperature resistant, ceramic and biological coatings can also be produced by raising the potential difference in the cells [42-44].

The following steps can be used to describe the process of particle integration in the metal matrix during electrodeposition: 1) particles move from the solution bulk to the metal surface, 2) particle adsorption on the electrode surface (interaction), and 3) particle embedding in the metal matrix as it grows. Guglielmi [45] presented the first model to account for the electrodeposition of metal reinforced with particles. According to this mechanism, the electrodeposition process is divided into two parts. To begin, van der Waals forces weakly adsorb particles on the cathode site, as a result of which there is a high level of surface covering as seen by the Langmuir adsorption isotherm. Second, under the effect of the supplied electric field, the particles are forcefully adsorbed on the surface and into the developing metal matrix by Coulomb forces. Figure 2 shows the schematic of several stages of strong and poor fixation adsorption arbitrarily on the electrode surface.

Celis [46] suggested a five-step model to explain the electrodepo-

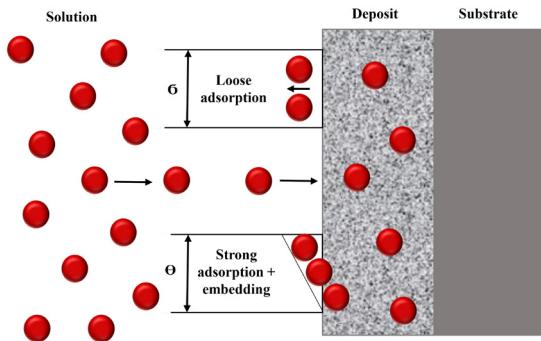


Fig. 2. The schematic of the process of co-deposition according to the Guglielmi model.

sition process: 1) the grains are surrounded by an ionic atmosphere, 2) particle mass movement to the hydrodynamic boundary layer via convection, 3) particles diffuse to the cathode surface by a diffusional mass movement, 4) electroactive ions and free ions are adsorbed on the grains here on the cathode, and 5) electro-reduction of adsorbed ions with particle integration into the expanding metal.

According to the Kurosaki model, mechanical agitation is used to move dispersed particles to the Helmholtz double layer in the prime stage [47]. In this model, electrophoresis is used to transfer charged particles to the cathode from a significant potential gradient. By the Coulomb attraction between adsorbed anions and particles on the cathode, the cathode surface has particles deposited on it in the third phase and incorporated into the developing metal layer [47].

Other models [20, 48] have been proposed, but additional research is needed to account for particle characteristics (composition, crystallinity, size, and so on) and operating electrodeposition parameters [48-50]. Figure 3 summarizes the most important procedure concerned with the particle electroplating into a metallic matrix in growth. .

#### 4. Essential components of Borides particles

Boron compounds are well valued due to features such as high Young's modulus, high hardness, and low density; nevertheless, their application is limited due to low fracture toughness, poor interability, and low wettability with most metals [51, 52]. To have a significant trend on B-based compositions, it is critical to identify the most practical synthesis method for the fabrication of B components. One of such methods is electroplating, which is applied to coat materials with a film of various metals. Despite the well-known useful properties of borides, such as hardness, supporting the metallic under-layer from wear, little research has been carried out on borides electrodeposition, and this area is still widely unknown. Possibly, the first methodical study was performed by Andrieux and Weiss (1940) [53]. Although this study led to more electro-synthesis process than electroplating, it illustrated that a lot of binary compounds could be fabricated through electrochemical methods by molten salts. Particularly, the compounds of molybdenum and tungsten were fabricated through electrolysis from molten salts of anti-monides, sulfides, arsenides, carbides, and borides. The composition of the bath was normally composed of alkali metal borate-fluoride combinations, which are great solvents for the tungsten and molybdenum oxides [53].

Kellner [54] investigated the impacts of a range of factors affecting the purity and quality of plated boron to improve the process. To produce a smooth, hard, and adherent deposit, he discovered that compounds based on oxygen, such as  $B_2O_3$ , should be strictly eliminated from the melt. His solvent was a 1:1 mixture of LiF-KF, with boron added as  $BF_3$  (g). The electroactive species is  $BF_4^-$  shown in equation (1), and the gas is very soluble. The temperature was 700 °C. A three-electron reduction

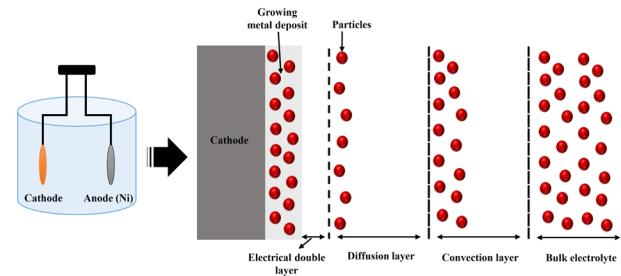
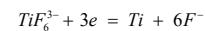
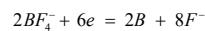


Fig. 3. The schematic procedure for co-electrodepositing unsolvable particles into a developing metal matrix to form a metal composite covering.

was confirmed by electrochemical and mass balance studies:



$TiB_2$  has received the most attention out of all the refractory borides. This is due to its excellent resistance to oxidation (even at 1000 °C), corrosion, and erosion in high-temperature concentrated brines, and the adhesion of coating and substrate. By adding  $BF_3$  to this melt, Kellner et al. [55] followed Kellner's research on boron plating from FLINAK. Titanium was included, but it was most likely converted to its fluoride type. The probable reactions at the cathode are shown in Equation (2):



Some of the research done is focused on the functional features of plating, created to prevent corrosion in valves and pipes employed to transport high-temperature, geothermal brines. As a result, only the overall reactions were given, despite the plating processes being cautiously examined and the characteristics of the coating being explored [53, 56, 57].

#### 5. Electrodeposition of Nickel matrix composite coatings via Boride particles

Coatings with adequate hardness and wear resistance are usually deposited on devices that are employed for harsh forming, cutting, and casting usages, wherever the process situations generally lead to elevated temperatures, enhanced mechanical loads, and increased wear [58-60]. Coatings consisting of hard Cr are noted due to their excellent corrosion and wear resistance; however, materials such as carbon-based materials, boride, oxides, carbides, and nitrides are also widely utilized in fabricating hard coatings because of their superior tribological and mechanical characteristics [61-64]. Despite having a promising mix of features that has drawn the attention of a growing number of researchers, the industrial applicability of boride-based thin films remains limited. The fact that the related bulk phases display promising features, such as chemical stability and high hardness, has sparked interest in boride coatings [65, 66]. In addition, wonderful oxidation resistance and chemical stability in harsh conditions are the recurrent characteristics of these materials [61].

A nickel-boron alloy layer can be created on the surface of a solid substrate, such as plastic or metal, using an electroless NiB coating technique [67]. Rajagopal et al. [68] discussed the composite coatings of Ni-B received by an electroplating process and electroless-based deposition from a bath of borohydride. The deposits of nickel created via chemical reduction and sodium borohydride are compounds of boron

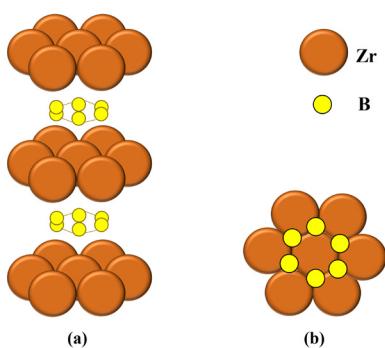


Fig. 4. The schematic of  $\text{ZrB}_2$  structural projection: a) 3D view and b) top view.

and nickel. The resistivity of heat-treated Ni-B composite coatings to electricity was almost similar to that of the electroplated nickel (about  $10 \Omega\text{m}$ ). Electroplated and electroless composite coatings of Ni-B had corrosion resistance greater than electroplated nickel because of soaking in  $\text{NaCl}$  solution. Individual electroplated and electroless Ni-B composite coatings once heated to  $400^\circ\text{C}$  present the most superior corrosion resistance to the Ni-B coatings that were plated in advance. The mentioned phenomenon results in the existence of the  $\text{Ni}_2\text{B}$  and  $\text{Ni}_3\text{B}$  phases, which could decrease the current density of local corrosion. Indeed, there was no mark of corrosion on the deposits of heat-treated Ni-B when being soaked about 100 h, while corrosion marks were ascertained for electroplated nickel with the same thickness (10  $\mu\text{m}$ ) after 20 h of the immersion test. The resistance of heat-treated, at  $400^\circ\text{C}$ , composite coatings of electroless and electroplated Ni-B to abrasion is  $3 \times 10^4 \frac{\text{mm}^3}{\text{hr}}$  vs.  $25 \times 10^4 \frac{\text{mm}^3}{\text{hr}}$  for a plated nickel. Further investigation revealed that the tensile properties and hardness of the electroplated Ni-B composite were larger than the as-deposited electroless composite of Ni-B. The superior characteristics of electroplated composites of Ni-B to electroless Ni-B coatings make it clear that electroplating could be a suitable approach for producing Ni-B composites [68].

#### 5.1. Electrodeposition of Nickel matrix composite coatings via $\text{ZrB}_2$ particles

Zirconium diboride ( $\text{ZrB}_2$ ) has a highly covalent refractory and hexagonal crystal shape ceramic material. It is a rare ceramic with strong thermal and electrical conductivities shared with isostructural titanium diboride and hafnium diboride. As shown in Figure 4, this system comprises layers of boron (B) atoms in two-dimensional graphite-like plates in  $\text{sp}^2$  hybridization with hexagonal close-packed (hcp) Zr arrays alternating [69].

$\text{ZrB}_2$  structure includes Zr-Zr metallic connections, B-B covalent linkages, and Zr-B covalent/ionic bonds. Zr-Zr bonds have strong electrical and thermal conductivities due to the existence of free electrons, which increase the hardness, stiffness, and chemical inertness properties of B-B bonds. The melting point of  $\text{ZrB}_2$  is raised due to the strong Zr-B bonds. In addition to its high melting point,  $\text{ZrB}_2$  has several unique properties, including high-temperature retention strength and slags, chemical inertness to molten metals, corrosion and erosion resistance in harsh environments, high thermal and electrical conductivities, low thermal expansion coefficient, and excellent thermal shock resistance.  $\text{ZrB}_2$  has also been shown to be resistant to plasma arcs and sparks [70-72].

Buichi ISE et al. [73] examined Ni- $\text{ZrB}_2$  composite coatings electrodeposited from Watt's bath in which  $\text{ZrB}_2$  particles were present. According to the results, the optimum plating condition for maximizing  $\text{ZrB}_2$  content was identified at  $5 \frac{\text{A}}{\text{dm}^2}$  and 900 rpm. The co-deposition rate of  $\text{ZrB}_2$  particles is dependent on the plating current density and plating solution stirring rate. In the range of  $10\text{-}20 \frac{\text{mg}}{\text{cm}^2}$ , a linear association was

discovered between  $\text{ZrB}_2$  content and the amount of deposited Ni- $\text{ZrB}_2$  composite.

Mellors and Senderoff [74] showed that electrolysis of the melt containing Flinak<sup>1</sup> 80 w/o ( weight percent) –  $\text{ZrF}_4$  8 w/o –  $\text{B}_2\text{O}_3$  12 w/o in a graphite crucible  $750^\circ\text{C}$  produced a smooth, dark-colored deposit at 100% cathode current efficiency, based on the assumption of  $10 \frac{\text{F}}{\text{mol}}$  of  $\text{ZrB}_2$ . The anode and the cathode were zirconium and a nickel strip, respectively. On raising the temperature to  $800^\circ\text{C}$ , a bright, coherent plate was obtained (at 100% cathode current efficiency) that was re-identified as  $\text{ZrB}_2$ . It will be noticed that there exists a considerable diffusion layer between the nickel substrate and  $\text{ZrB}_2$ . The mentioned layer is a nickel boride, from which zirconium is absent. By the same token, nickel is absent from the  $\text{ZrB}_2$  deposit. This indicates that some boron diffuses into nickel from the initially deposited  $\text{ZrB}_2$ , resulting in a deposit at the interface having a B: Zr ratio slightly less than 2. The electron probe analysis indicates that the intermediate layer is, in all probability,  $\text{Ni}_3\text{B}$ , and it is thought that the presence of this material contributes to the adherence of  $\text{ZrB}_2$  to the substrate.

Huang et al. [75] showed that certain compounds (e.g.  $\text{TiC}$ ,  $\text{ZrB}_2$ , and  $\text{TiB}_2$ ) were recognized for possessing adequate thermal and electrical conductivities as well as hardness. It was shown that hard particles with electrical conductivity could impact the stability of electroless nickel plating bath in a way that  $\text{TiB}_2$  and  $\text{ZrB}_2$  had significant and the least important effects, respectively. Moreover, this boride  $\text{ZrB}_2$  is stable at high temperatures and resistant to molten metals, molten salts, and atmospheric oxidation, rendering it an appropriate material for protection applications in harsh conditions.

#### 5.2. Electrodeposition of Nickel matrix composite coatings via $\text{TiB}_2$ particles

A high melting point ( $3225^\circ\text{C}$ ), high-temperature strength, high thermal conductivities, hardness, and wear resistance are all characteristics of titanium diboride ( $\text{TiB}_2$ )-based materials. As a result, they are excellent for cutting tools, electrode materials, and wear-resistant coatings that require extreme environmental conditions and service temperatures of more than  $2000^\circ\text{C}$ . Because monolithic  $\text{TiB}_2$  has a poor oxidation resistance over  $1000^\circ\text{C}$ , additives have been employed to improve its oxidation behavior at high temperatures [76-78].

Gyawali et al. [79] fabricated Ni- $\text{TiB}_2$  coatings by pulse electrodeposition techniques from nickel sulfamate bath containing dispersed sub-micron  $\text{TiB}_2$  particles. The results showed a greater Vickers' microhardness of around 690 HV in the composite coating fabricated from  $\text{TiB}_2$  particles in the electrolyte. This level of microhardness is around three times greater than that of the pure nickel coating (230 HV). Moreover, composite coatings have illustrated a positive shift in corrosion potential of  $E_{\text{corr}} = -0.2692 \text{ V}$  compared with that of nickel, which is equal to  $-0.3117 \text{ V}$ . The presence of an extended passive section together with a positive charge of corrosion potential for the composite coatings can be associated with the variety in the crystal structure of the nickel matrix and modified grain size, as well as implemented  $\text{TiB}_2$  particles that probably behaved as an interior physical barrier against the development of corrosion, therefore, enhancing the polarization resistance of the composite layer.

To increase the performance of Ni- $\text{TiB}_2$ - $\text{Dy}_2\text{O}_3$  composite coatings, Liu et al. [80] employed  $\text{TiB}_2$  and  $\text{Dy}_2\text{O}_3$  as co-deposited particles. Electrodeposition of a hexadecyl pyridinium bromide and nickel cetyltrimethylammonium bromide solution containing  $\text{TiB}_2$  and  $\text{Dy}_2\text{O}_3$  particles yielded Ni- $\text{TiB}_2$ - $\text{Dy}_2\text{O}_3$  composite coatings. According to the findings, wear losses of mass of Ni- $\text{TiB}_2$ - $\text{Dy}_2\text{O}_3$  matrix coatings were 9

<sup>1</sup> “Flinak” is the acronym for the eutectic composition of KF-LiF-NaF that melts at  $454^\circ\text{C}$ . Its composition in mole per cent is 46.5 LiF, 11.5 NaF, and 42.0 KF.

and 1.57 times smaller than pristine Ni and Ni-TiB<sub>2</sub> composite coatings, respectively. The friction coefficients of pristine Ni, Ni-TiB<sub>2</sub>-Dy<sub>2</sub>O<sub>3</sub>, and Ni-TiB<sub>2</sub> composite coatings were 0.723, 0.619, and 0.815, respectively. Among the three coatings, Ni-TiB<sub>2</sub>-Dy<sub>2</sub>O<sub>3</sub> composite coatings had the lowest friction coefficient.

Gyawali et al. [81] used electrodeposition to create Ni-W-TiB<sub>2</sub> composite coatings on the copper substrate. The Vickers micro-hardness of Ni-W-TiB<sub>2</sub> composite coatings was much higher than pure Ni and Ni-W alloy coatings, along with enhanced wear and coefficient of friction in the Ni-W-TiB<sub>2</sub> composite coating. Adhesive wear is significant in pure Ni and Ni-W coatings, whereas abrasive wear is observed in Ni-W-TiB<sub>2</sub> composite coatings. The scratch resistance of the composite coating was better than pure nickel and Ni-W coatings. W alloying and TiB<sub>2</sub> inclusion into the nickel matrix affected the scratch resistance of the composite coating.

### 5.3. Electrodeposition of Nickel matrix composite coatings via BN particles

Boron nitride (BN) is a boron-nitrogen refractory substance with the chemical formula BN that is thermally and chemically resistant. It appears in a variety of crystalline forms that are isoelectronic to a carbon lattice with a comparable structure. BN ceramics have long been employed as parts of high-temperature equipment due to their superior chemical and thermal stability. Nanotechnology could benefit from BN [82, 83]. Because of their wear resistance and high hardness, Ni-BN composites are significant for a variety of applications. The metal matrix particle measurement is unaffected by BN particles [84, 85].

Pompei et al. [5] electrodeposited nickel–boron nitride (Ni–BN) composites from a sulfate bath containing up to 10  $\frac{g}{l}$  of dispersed bo-

ron nitride particles. The surfactants in the plating solution improve the micro-hardness of the deposit, from 280 to about 400 HV. The improvement in micro-hardness of the composite coating can be because of (a) the dispersive strengthening effect of h-BN, (b) inhibited crystalline growth by h-BN nano-sheets in the coatings in the electrodeposition procedure, thereby refining nickel crystallites, and (c) hindering the movement of dislocations and the sliding of grain boundary by h-BN nano-sheets. Besides, the results clarify the improvement of corrosion protection by h-BN reinforcement in the nickel matrix.

Tripathi et al. [86] investigated Ni-Fe alloy matrix nanocomposite coatings containing uniformly dispersed 24 wt. % BN particles. The results showed that the hardness levels of as-deposited and heat-treated nanocomposite coatings were significantly higher than that of the substrate. A correlation between crystallite size and strain with hardness was worked out in their research.

Li et al. [87] investigated the pulse electrodeposition of functionally graded (FG) Ni-W/BN(h) nanocomposite coatings with varying BN(h) nanoparticle content along with the thickness. The findings demonstrated that the content of BN(h) nanoparticles and tungsten grew to various degrees as the frequency or duty cycle was reduced along with the four-layer structure. In addition, FG Ni-W/BN(h) coatings had much better wear resistance and microhardness than uniform Ni-W/BN(h) coatings. Furthermore, the presence of more BN(h) nanoparticles in the deposits improved the corrosion resistance in FG coatings.

### 5.4. Electrodeposition of Nickel matrix composite coatings via another boride particles

As with many other transition metal borides, chromium diboride (CrB<sub>2</sub>) is an inorganic compound that is exceedingly strong and hard

**Table 1.**

Bath elements of Ni-B alloy matrix composite coatings

Composite coatings	Boron source and content ( $\frac{g}{l}$ )	Nickel source and content ( $\frac{g}{l}$ )	Particle type, content ( $\frac{g}{l}$ )	Results	Ref.
Ni-B/CeO <sub>2</sub>	DMAB*, 3	NiSO <sub>4</sub> ·6H <sub>2</sub> O-240 NiCl <sub>2</sub> ·H <sub>2</sub> O-45	CeO <sub>2</sub> , 15	The surface roughness, hardness, modulus of elasticity, and corrosion behavior of Ni-B corrosion improved with the addition of CeO <sub>2</sub> .	[95]
Ni-B/TiO <sub>2</sub>	DMAB, 3	NiSO <sub>4</sub> ·6H <sub>2</sub> O-250 NiCl <sub>2</sub> ·H <sub>2</sub> O-40	TiO <sub>2</sub> , 50	When compared to NiB coating, Ni-B/TiO <sub>2</sub> coating has a better surface hardness, wear resistance, and resistance to corrosion.	[96]
duplex Ni-B-TiO <sub>2</sub> /Ni	DMAB, 3	NiSO <sub>4</sub> ·6H <sub>2</sub> O-250 NiCl <sub>2</sub> ·H <sub>2</sub> O-40	TiO <sub>2</sub> , 50	This coating showed high hardness and good corrosion resistance properties.	[97]
Ni-B/Al <sub>2</sub> O <sub>3</sub>	DMAB, 3	NiSO <sub>4</sub> ·6H <sub>2</sub> O-240 NiCl <sub>2</sub> ·H <sub>2</sub> O-45	Al <sub>2</sub> O <sub>3</sub> , 15	The surface roughness, hardness, modulus of elasticity, and corrosion behavior are significantly improved with the addition of Al <sub>2</sub> O <sub>3</sub> in Ni-B coating.	[98]
Ni-B/La <sub>2</sub> O <sub>3</sub>	DMAB, 5	NiSO <sub>4</sub> ·6H <sub>2</sub> O-280	La <sub>2</sub> O <sub>3</sub> , 5-10	The thermal stability of metastable Ni-B coatings improved with the addition of La <sub>2</sub> O <sub>3</sub> .	[99]
Ni-B/V <sub>2</sub> O <sub>5</sub> -ZrO <sub>2</sub>	DMAB, 3	NiSO <sub>4</sub> ·6H <sub>2</sub> O-240 NiCl <sub>2</sub> ·H <sub>2</sub> O-45	V <sub>2</sub> O <sub>5</sub> -ZrO <sub>2</sub> , 0.75+0.75	The Ni-B coating's hardness, surface roughness, and modulus of elasticity are almost 70-170 percent higher.	[100]
Ni-B/Fe <sub>2</sub> O <sub>3</sub>	DMAB, 3	NiSO <sub>4</sub> ·6H <sub>2</sub> O-240 NiCl <sub>2</sub> ·H <sub>2</sub> O-45	Fe <sub>2</sub> O <sub>3</sub> , 15	The results showed a 52% improvement in hardness and good corrosion protection in Ni-B coating with Fe <sub>2</sub> O <sub>3</sub> .	[101]
Ni-B/Diamond	TMAB †, 3	NiSO <sub>4</sub> ·6H <sub>2</sub> O-240 NiCl <sub>2</sub> ·H <sub>2</sub> O-45	Diamond, 5-50	Extremely high hardness is obtained with the addition of diamond.	[102]
Ni-B/Y <sub>2</sub> O <sub>3</sub>	DMAB, 3	NiSO <sub>4</sub> ·6H <sub>2</sub> O-240 NiCl <sub>2</sub> ·H <sub>2</sub> O-45	Y <sub>2</sub> O <sub>3</sub> , 9	The superior thermal stability and improvement of mechanical and anti-corrosion properties (73.6%) are obtained with the addition of Y <sub>2</sub> O <sub>3</sub> on Ni-B coating.	[103]
Ni-B/TiC-Y <sub>2</sub> O <sub>3</sub>	DMAB, 3	NiSO <sub>4</sub> ·6H <sub>2</sub> O-240 NiCl <sub>2</sub> ·H <sub>2</sub> O-45	Y <sub>2</sub> O <sub>3</sub> , 9 and TiC, 15	The findings showed adding TiC-Y <sub>2</sub> O <sub>3</sub> to Ni-B coating improves surface roughness, wear, and corrosion resistance (30%).	[104]

\*DMAB: Dimethylamine borane

†TMAB: Trimethylamine borane

and transmits electricity and heat similar to many metallic alloys, with a high melting point [88]. Nozdrin et al. [89] studied the features of the electrical deposition of nickel-based composite coatings, which contain  $\text{CrB}_2$  nano-powder as a strengthening phase. With the existence of the nano-dispersed phase, the maximum limit of the working density of the electrolyte current is  $1.0 \frac{KA}{m^2}$ , which is greater than that for achieving nickel coatings in this electrolyte ( $0.5 \frac{KA}{m^2}$ ). The micro-hardness of the  $\text{Ni-CrB}_2$  nanocomposite is recognized by the quantity of the  $\text{CrB}_2$  nanoparticles. The coating obtained at cathode current densities of 0.1, 0.5, and  $1.0 \frac{KA}{m^2}$  have micro-hardness values of 2.86, 3.29, and 4.44 GPa, respectively, which are higher than those obtained for the nickel matrix at  $j_c=0.5 \frac{KA}{m^2}$  by a factor of 1.41, 1.62, and 2.19.

Rare earth oxides (such as  $\text{CeO}_2$ ) exhibit exceptional properties in MMC coatings, preventing cracks, defects, and pores. Compared to pure Ni coatings, it can also improve corrosion resistance [90, 91]. On the substrate of steel, Wang et al. [92] utilized pulsed electrodeposition to produce Ni-W-B composites containing  $\text{CeO}_2$  nanoparticles. The results showed that pulse co-deposition of Ni, W, B, and  $\text{CeO}_2$  nanoparticles resulted in Ni-W-B/ $\text{CeO}_2$  composites with increased micro-hardness and superior wear resistance after being heat-treated at 400 °C for 1 h. The as-deposited alloy exhibited a maximum surface hardness of 636 HV, a deposition rate of  $0.0281 \frac{mm}{h}$  at a frequency of 1000 Hz, a pulsation duty circle of 10%, and a pulse-estimated average density of  $10 \frac{A}{dm^2}$ . The formed composites were largely amorphous and somewhat crystalline, and the crystallization tendency was enhanced when they were exposed to 400 °C. The refinement of the development and grain structures of microstructures were aided by lowering. The pulsed switching frequency was reduced from 75% to 10%. Pulse electrodeposition was used to reduce the crystal sizes of the composites.

Among the numerous ceramic particles, boron carbide ( $\text{B}_4\text{C}$ ) particles are one of the most promising reinforcing particles because they have unique physical-mechanical characteristics that make them ideal for abrasive grit and wear-resistant components.

Using pulsed electrodeposition, He et al. [93] created a Ni-W- $\text{B}_4\text{C}$  MMC coating with only the  $2 \frac{g}{l} \text{B}_4\text{C}$  concentration. According to the findings, applying  $\text{B}_4\text{C}$  nanoparticles to the Ni-W alloy substantially enhanced the micro-hardness and substrate morphology of matrix coating. Ni-W- $\text{B}_4\text{C}$  nanocomposite has a substantially higher corrosion resistance than Ni-W alloy deposits.

Table 1 presents the elements of the composite coating bath and the Ni-B matrix. The dimension of the strengthening element could be in the range of micron or nano. Table 1 demonstrates that a variety of oxides, nitrides, carbides, nitrides, and oxides are employed as reinforcing elements, and even though the size of particles is quite paramount; some studies present no results regarding the sizes of the strengthening inert particles [94].

## 6. Conclusions

The composite coating based on Ni, which is a very effective method, may be used to modify the surface of components. Since surface engineering can be described as a novel approach, it is still in the early stages of development. According to a review of the literature, the Ni-based MMC coating gives the area a very high strength, which improves wear resistance.

The presence of Ni also demonstrates good corrosion resistance. However, the review shows that only Ni alloy or Ni coatings are not as effective as Ni-based composite coatings. Plasma spraying, thermal, chemical, and physical vapor deposition have all been considered as methods for preparing nanocomposite materials. When compared to other electrodeposition methods, precision management, uniform deposition, low energy needs, low cost in producing wide-area samples, great

versatility, reproducibility, ability to coat complex component configurations, waste reduction, and increased efficiency are only some of the benefits. A wide range of particles have been used in nickel matrix electrodeposits, including oxides such as  $\text{SiO}_2$ ,  $\text{TiO}_2$ ,  $\text{Al}_2\text{O}_3$ ,  $\text{SnO}_2$ ,  $\text{ZrO}_2$ ,  $\text{CeO}_2$ , and  $\text{Cr}_2\text{O}_3$ , carbides such as WC, SiC, and TiC nitrides such as carbon nanotubes and BN,  $\text{Si}_3\text{N}_4$ , and so on. Boride ceramic particles have recently been used in a variety of MMCs. The results of mechanical properties, wear, and corrosion in these composites show that boride particles have a significant impact on improving these properties.

This study examines Ni-based composite coatings, the concept of electrodeposition methods, the behavior of boride particles in composites, and the literature on nickel matrix composite coatings reinforced with boride ceramics particles. Furthermore, it appears that further studies are required in this sector to fully understand the behavior of various boride particles in Ni-based composite coatings.

## Acknowledgments

The authors received no financial support for the research, authorship and/or publication of this article.

## Conflict of interest

The authors declare that there is no conflict of interest.

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