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Review

A Comprehensive Review on Aluminide Coatings for Ni-Based Superalloys: From Processing to Performance

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Abstract

In this review, a comprehensive analysis of aluminide coatings for nickel-based superalloys was performed with the particular emphasis on their processing, microstructural evolution, and performance under high-temperature conditions. Nickel-based superalloys are widely used in power engineering and aerospace industries; however, their susceptibility to oxidation and hot corrosion necessitates advanced surface protection strategies. Aluminide coatings offer effective protection through the formation of stable and adherent alumina scales. The review systematically evaluates major deposition techniques, including chemical vapour deposition (CVD), pack cementation, slurry aluminizing, and advanced hybrid methods, highlighting their influence on coating structure and properties. Special attention is given to the relationship between processing parameters, microstructure, and functional performance, including oxidation resistance, corrosion behaviour, and mechanical properties such as hardness and fatigue life.

Keywords: aluminide coatings; nickel-based superalloys; chemical vapour deposition; pack cementation; slurry aluminizing; high-temperature oxidation

1. Introduction

Nickel-based superalloys are frequently used for advanced engineering systems operating under extreme thermal and mechanical loads, particularly in aerospace, power generation, and automotive applications [1]. Their superior mechanical properties, maintained even at high temperature, and microstructural stability make them the material of choice for various components including turbine blades, combustors, and exhaust systems [2]. However, the continuous demand for higher operating temperatures and improved efficiency has exposed a critical limitation including limited high-temperature oxidation and hot corrosion resistance in aggressive environments [3]. Under such conditions, rapid oxide scale growth, depletion, and surface degradation can significantly reduce component lifetime and reliability.

To address these challenges, surface engineering strategies have become crucial to extending the service performance of nickel-based alloys. Among these, aluminide coatings have emerged as one of the most effective and promising solutions. These coatings, typically based on NiAl intermetallic phases, are widely applied using techniques such as chemical vapour deposition, pack cementation, and slurry aluminizing [4]. Their technological relevance comes from their ability to provide a protective aluminum-rich surface layer that alters the degradation mechanisms of the underlying alloy.

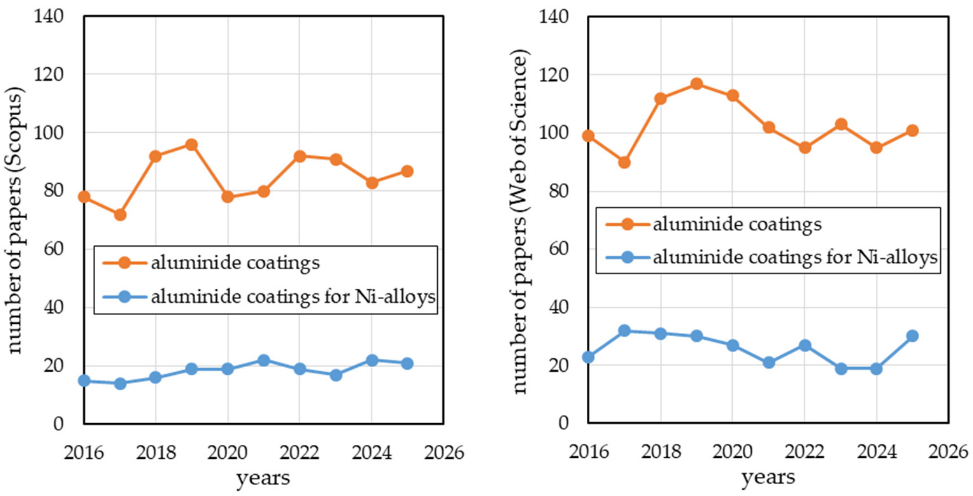
Received: 30 March 2026
Revised: 14 April 2026
Accepted: 20 April 2026
Published: 21 April 2026

https://doi.org/10.3390/coatings16040506

A key advantage of aluminide coatings is that they can form a dense and well adherent scale during high-temperature exposure [5]. Such thermodynamically stable alumina oxide is used as an effective diffusion barrier, as it limits oxygen diffusion and suppresses further oxidation of the substrate [6]. As a result, coated systems exhibit significantly enhanced oxidation resistance, even under cyclic or isothermal high-temperature conditions (typically 900–1200 °C), compared to uncoated alloys [7]. Furthermore, compositional modifications and interactions with substrate elements can promote the growth of the α-Al_2O_3 phase, which in turn leads to improved scale adherence and long-term durability.

Beyond oxidation protection, aluminide coatings contribute substantially to the mechanical performance of nickel-based alloys at elevated temperature [8]. The formation of β-NiAl phases enhances surface hardness and wear resistance, while also improving fatigue life by mitigating surface-initiated damage mechanisms. In addition, the coatings can influence stress distribution and delay crack initiation under thermomechanical loading, thereby extending component lifespan under cyclic loading. It should also be stressed that the effectiveness of these improvements depends also on coating–substrate adhesion, interdiffusion behaviour, and microstructural stability during service [2].

Despite their well-established benefits, the transition of aluminide coatings from laboratory-scale research to large-scale industrial implementation presents several challenges. These include process scalability, reproducibility, cost efficiency, and the ability to tailor coating composition and microstructure for specific applications. Comparative analysis of the scientific output related to aluminide coatings for nickel-based alloys based on two major bibliographic databases: Scopus and Web of Science have shown moderate interest in aluminide coatings over recent years (Figure 1).



(**a**) (**b**)

Figure 1. Cross-database comparison of publications on aluminide coatings and aluminide coatings for nickel-based alloys in Scopus (**a**) and Web of Science (**b**).

The observed stable trend reflects the continued efforts to develop advanced surface engineering solutions that may further improve the nickel-based superalloys' performance in aggressive environments and under high temperature. These trends correlate with the expanding demand for coatings with enhanced oxidation resistance, as well as with improved mechanical properties including fatigue life, hardness, and resistance to thermomechanical degradation in the presence of complex service conditions such as thermal cycling, corrosive atmospheres, and multiaxial stresses [9].

In this context, aluminide coatings for nickel-based alloys were discussed, with a particular focus on their role in enhancing high-temperature mechanical performance and oxidation resistance. Special emphasis is placed on recent advances in coating design, deposition technologies, and degradation mechanisms, as well as the critical factors governing their industrialization. By bridging the gap between the fundamental materials science summarized in the authors' previous review [4] and practical engineering requirements, this review seeks to outline the pathways toward reliable, cost-effective, and scalable deployment of aluminide coatings in next-generation high-temperature systems. This review also aims to address the following research question: how do different aluminide coating deposition technologies influence the microstructure–property relationships governing high-temperature performance of nickel-based superalloys? The scope is focused on systematically comparing major processing routes (CVD, pack cementation, slurry, and hybrid methods) and linking them to oxidation resistance, corrosion behaviour, and mechanical performance. The novelty of this work lies in its integrated approach, which summarizes recent studies (2023–2026) and also establishes direct relationships between processing, microstructure, and performance, while highlighting critical trade-offs and identifying current research gaps.

2. Methodology

This article offers a structured evaluation of recent investigations into aluminide coatings, highlighting fabrication techniques and behaviour under elevated-temperature conditions. Relevant sources were identified through searches conducted in the Web of Science, Scopus, and ScienceDirect platforms. Only peer-reviewed journal papers and conference contributions issued between 2023 and 2026 were considered. This limited period was chosen to capture the latest developments following earlier reviews in this research area [4]. The query strategy emphasized the terms "aluminide coatings" and "nickel-based alloys," together with closely related expressions. An initial pool of 280 records was obtained. Each entry then underwent a relevance check based on titles, abstracts, and, when required, full texts, guided by predefined selection criteria. After this filtering stage, 95 publications were retained as most pertinent and formed the basis for detailed examination and discussion.

3. Performance of Aluminide Coatings on Nickel-Based Alloys in Relation to Deposition Technology

3.1. Chemical Vapour Deposition

CVD provides the most comprehensive improvement in both mechanical performance and high-temperature environmental resistance, primarily due to excellent coating uniformity, strong metallurgical bonding, and controlled diffusion kinetics as shown in Table 1.

Table 1. Overview of modern CVD aluminide coatings applied to nickel-based alloys [10–28].

Coating	Substrate Material	Main Advantages	Ref.
NiAl	Inconel 939	improved hardness (954 ± 96 HV) as compared to the substrate (440 ± 32 HV), potential high-temperature applications	[10]
PtAl	third-generation SX superalloy	high-cycle fatigue (HCF) life of the thermally-exposed (1100 °C for 100 and 250 h) coated alloy increased (test at 900 °C, σ_{max} = 520 MPa)	[11]
NiAl/AlY/PtAl	MAR-M247	Y/Pt increased NiAl corrosion resistance, improved α-Al_2O_3 scale adhesion and density and reduced internal attack in NaCl-humid air at 750 °C	[12]

https://doi.org/10.3390/coatings16040506

Table 1. *Cont.*

Coating	Substrate Material	Main Advantages	Ref.
NiAl	MAR-M247	fine-grain substrates exhibiting the least resistance changes and greatest fatigue response; 20 µm coatings showed better fatigue resistance than 40 µm coatings	[13]
NiAl	IN713 IN625 CMSX4	the lifetime of coated IN713 and IN625 superalloys was comparable; the IN713 and IN625 oxidation resistance (at 100 °C for 400 h) was significantly better than CMSX4	[14]
NiAl	AM IN939	improved high-temperature cyclic oxidation (at 1050 °C for up to 240 cycles—20 min heating/50 min holding/15 min cooling to RT)	[15]
Ni_2Al_3	DD6	The CVD aluminide coating on DD6 exhibited a higher oxidation rate in air at 1000 °C for 20 h than on Ni	[16]
NiAl	K452	coatings formed at 1050 °C showed better resistance to NaCl–air–H_2O exposure at 750 °C (10 h); higher deposition temperature promotes fewer grain boundaries, which effectively reduces active oxidation	[17]
NiAl	Inconel 718/MAR-M247	Fe in Inconel 718 coatings promoted transition to stable α-Al_2O_3, enhancing oxidation resistance in air at 950 °C	[18]
NiAl	MAR-M247	Fine-grained MAR-M247 improved fatigue resistance via uniform strain; coarse and columnar grains promoted strain localization and early cracking	[19]
NiAl	MAR-M247	significantly improved corrosion resistance of MAR-M247 in Na_2SO_4-induced hot corrosion test at 750 °C, 850 °C and 950 °C for 50 h	[20]
NiAl	$Ni_{0.25}Co_{0.25}Cr_{0.22}Mo_{0.14}Re_{0.14}$	notably improved high-temperature oxidation resistance (200 h at 1150 °C)	[21]
NiAl	MAR-M247	20 µm and 40 µm coatings showed similar fatigue life at 900 °C under 400–520 MPa stress amplitude	[22]
NiAl/NiFe	K444	Y-modified aluminide coatings outperformed single aluminide in cyclic oxidation at 1100 °C, same as the resistance to heat corrosion (at 900 °C in NaCl + Na_2SO_4)	[23]
NiAl/Hf	IN 713C	improved corrosion resistance	[24]
NiAl	Inconel 718	the aluminide coating significantly improves the corrosion resistance of Inconel 718 alloy (at 750 °C in air + NaCl, and air + NaCl + water vapour environment)	[25]
NiAl	K444	aluminide coating reduces oxidation and Na_2SO_4 corrosion, improving high-temperature resistance (750–950 °C) of substrate	[26]
NiAl	K403	higher β-NiAl bond coat purity and reduced IDZ improved high-temperature aero-engine performance	[27]
NiAl	Pure nickel/CMSX-4	Pd + Rh addition reduced oxidation rate; Pt + Rh coating gained ~0.3 mg/cm^2 after 170 h in air, lower than Hf- and Zr-modified variants (by 0.05 and 0.09 mg/cm^2)	[28]

CVD aluminide coatings significantly enhance surface hardness and fatigue resistance. The formation of β-NiAl phases leads to substantial strengthening, as demonstrated for Inconel 939, where hardness increased by nearly two times compared to the substrate [10]. This improvement directly translates into better wear resistance and reduced surface damage under cyclic loading. Furthermore, fatigue behaviour is strongly influenced by coating thickness and substrate microstructure. Studies on MAR-M247 show that thinner coatings (~20 µm) provide superior fatigue resistance compared to thicker ones due to reduced stress concentration and improved strain accommodation [13]. Grain refinement in the substrate further enhances fatigue life by promoting homogeneous deformation and delaying crack initiation [19]. CVD coatings also improve high-temperature mechanical stability, particularly under thermomechanical fatigue conditions. Pt-modified aluminide coatings on single-crystal superalloys significantly extend high-cycle fatigue life after thermal exposure by stabilizing the coating–substrate interface and suppressing microcrack formation [11]. This indicates that coating chemistry and deposition route directly influence damage evolution mechanisms at elevated temperatures. In terms of oxidation resistance, CVD coatings are highly effective due to the formation of α-Al_2O_3 scales. These scales act as diffusion barriers, significantly reducing oxygen diffusion and slowing degradation kinetics. The effect is particularly pronounced in additively manufactured materials, where CVD aluminizing dramatically improves cyclic oxidation resistance of IN939 under repeated thermal cycling [15]. The role of substrate composition is also critical; for example, Fe in Inconel 718 promotes transformation to stable α-Al_2O_3, further enhancing oxidation resistance [18]. Regarding corrosion performance, CVD coatings provide excellent protection in aggressive environments such as NaCl- and Na_2SO_4-containing atmospheres. Alloying additions (Y, Pt, Hf) improve scale adhesion, reduce spallation, and suppress internal corrosion mechanisms [12,24]. Process parameters such as deposition temperature are equally important since higher temperature produce coatings with fewer grain boundaries, reducing diffusion paths for corrosive species and improving resistance to hot corrosion [17].

One should highlight that although aluminide coatings provide effective protection against high-temperature oxidation and corrosion, their performance can be significantly enhanced through careful compositional design and optimization of processing parameters. The incorporation of reactive elements such as yttrium, hafnium, or zirconium can improve the adhesion and stability of the thermally grown α-Al_2O_3 scale by reducing spallation and suppressing the formation of detrimental defects at the oxide–coating interface [23,24]. Yang et al. [23] demonstrate that the addition of yttrium does not change the typical two-layer structure but increases aluminum content and coating thickness, with deposition temperature having a more pronounced effect (up to ~33% increase at 1050 °C). This improvement is reflected in enhanced oxidation and hot corrosion resistance, with up to ~45% lower mass gain during cyclic oxidation. As shown in Figure 2, these enhancements are also evident in surface morphology after hot corrosion testing. The single aluminide coating exhibits severe degradation with corrosion holes (Figure 2a), whereas yttrium-modified coatings show progressively improved surface integrity with increasing deposition temperature—from localized pits at 950 °C (Figure 2b) to dense, defect-free surfaces at 1000 °C and 1050 °C (Figure 2c,d). Combined with compositional analysis, one should conclude that higher deposition temperatures promote the formation of stable, protective oxide scales and suppress sulphur-induced degradation.

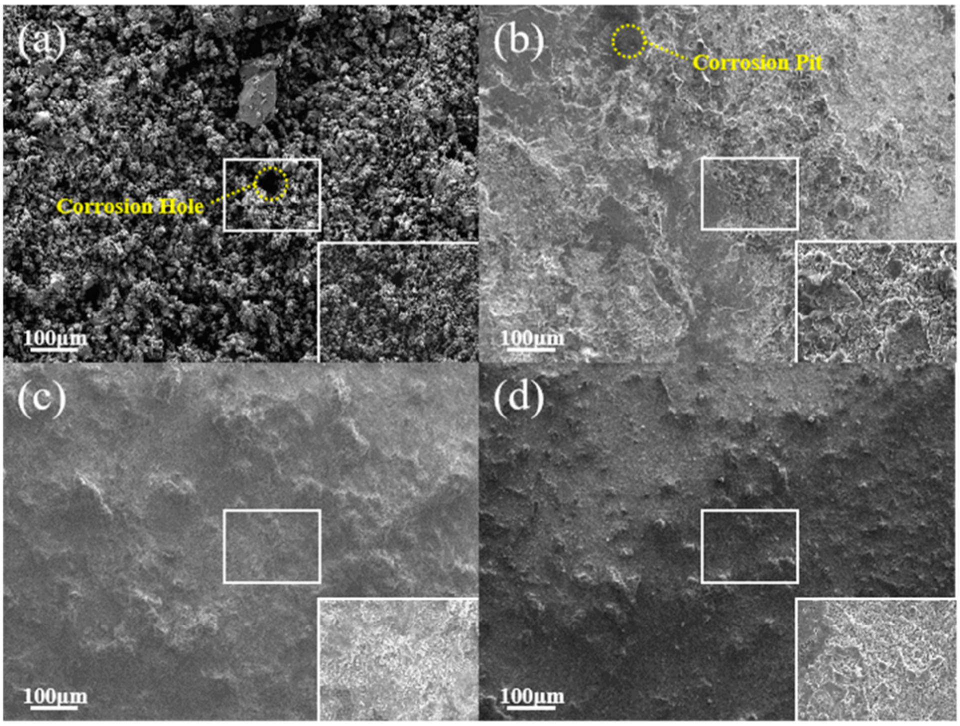


Figure 2. Morphological comparison of (**a**) single aluminide and Y-modified coatings on K444 alloy deposited at (**b**) 950, (**c**) 1000, and (**d**) 1050 °C following corrosion at 900 °C (Na_2SO_4 + NaCl) for 75 h [23].

3.2. Pack Cementation

Pack cementation significantly enhances high-temperature performance and oxidation resistance, while also improving mechanical properties. The summary of the recent advances in aluminide coatings for nickel-based alloys produced by pack cementation is presented in Table 2.

Table 2. Overview of recent improvements in pack cementation aluminide coatings on nickel alloys [29–39].

Coating	Substrate Material	Main Advantages	Ref.
Ni_3Al	HT700	enhanced corrosion resistance at 700 °C for 200 h	[29]
$NiAl/Ni_2Al_3$, Cr_2Al, and MoAl	Arc-DED Inconel 625	stable layers acted as diffusion barriers and increased hardness (1310 ± 32 HV0.1 vs. 225 ± 10 HV0.1)	[30]
$NiAl/Ni_2Al_3/Ni_3Al$	K447A	high temperature oxidation resistance at 1150 °C for 100 h	[31]
Al_3Ni_2/Al_5FeNi	Inconel 625	180 µm coatings showed strong supercritical oxidation resistance (500 °C, 25 MPa, 72 h)	[32]
$PtAl_2$/(Ni-Pt)Al	Inconel 738LC	Pt–Al coatings on Ni outperformed Pt–Rh–Al coatings on Co at 1050 °C for 200 h	[33]
$NiAl/NiAl/Cr_{0,1}Si_{0,9}$	IN718	Si-modified coatings had minimal mass gain (0.1 mg/cm^2) after 1000 °C/200 h exposure	[34]
NiAl, Ni_2Al_3, Cr_2Al, $MoAl_5$	Inconel 625	aluminide coating improved oxidation resistance by 6.63×, 2.70×, and 2.65× at 1000 °C (5, 25, and 50 h), with hardness of 12.85 ± 0.43 GPa and elastic modulus of 130.47 ± 3.38 GPa	[35]

Table 2. *Cont.*

Coating	Substrate Material	Main Advantages	Ref.
Ni_2Al_3/ZrO_2	Ni-ZrO_2	reduced oxidation rate at 900 °C for 20 h and improved interfacial strength	[36]
NiAl	ZHS32	enhanced high-temperature protection and β-NiAl nanomechanical performance in the rejuvenated sample (nanohardness 160.34 ± 0.01 GPa, microhardness 448 ± 11 HV, elastic modulus 131.45 ± 0.01 GPa)	[37]
NiAl	CMSX-4	diffusion aluminide coating showed lower mass change and superior oxidation resistance compared with HVOF NiCoCrAlY under 1100 °C cyclic exposure (300 cycles, 1 h with 15 min cooling)	[38]
$NiAl/Ni_2Al_3/Al_{13}Cr_2/Cr_5Si_3$	K438	Si-modified aluminide coatings showed reduced oxidation rate, improved Al_2O_3 scale adhesion, and extended protection in air at 1100 °C (stable up to 300 h)	[39]

One should note that pack-aluminized coatings produce very high surface hardness due to the formation of intermetallic phases such as NiAl and Ni_2Al_3. For example, aluminized Inconel 625 shows a dramatic increase in hardness (over 1300 HV) compared to the substrate (~225 HV), which substantially improves wear resistance and load-bearing capacity [30]. Additionally, the increase in elastic modulus contributes to better resistance to plastic deformation at elevated temperature [35]. However, due to the relatively thick and sometimes brittle nature of these coatings, there is a potential trade-off with ductility and fatigue resistance. In terms of high-temperature oxidation performance, pack cementation is highly effective. The thick aluminide layers enable continuous formation of protective alumina scales even under prolonged exposure (e.g., 100–300 h at temperatures above 1000 °C) [31,38]. This results in significantly reduced mass gain and slower oxidation kinetics compared to uncoated substrates. The oxidation resistance can be further enhanced through compositional modifications. Silicon additions reduce oxidation rates and improve scale adhesion, while Pt-modified coatings show superior performance at very high temperatures (e.g., 1050 °C) [33,34]. Additionally, nanocomposite approaches (e.g., ZrO_2 additions) improve interfacial strength and reduce oxide scale spallation [36]. Regarding corrosion resistance, pack-aluminized coatings provide strong protection against aggressive environments by acting as diffusion barriers. Multiphase coatings (e.g., NiAl + Cr_2Al + MoAl) limit the ingress of corrosive species and significantly improve resistance to hot corrosion and molten salts [30].

3.3. Slurry Aluminizing

Slurry aluminizing offers a flexible approach to improving high-temperature corrosion resistance and mechanical performance, particularly through compositional tailoring (Table 3).

Table 3. Overview of recent improvements in slurry aluminizing for nickel alloys [40–46].

Coating	Substrate Material	Main Advantages	Ref.
AlSi/CrSiAl	Rene-80	CrSiAl-E and CrSiAl-P showed better corrosion resistance than Al–Si aluminide coatings, maintaining a stable protective oxide scale under hot corrosion (20 cycles in Na_2SO_4 at 900 °C with air exposure)	[40]
NiAl/Cr precipitates	Inconel 690/ Inconel 617	Excellent oxidation and corrosion resistance, high wear resistance from hard intermetallic phases, thermally stable NiAl and Cr-rich layers, and improved high-temperature corrosion resistance of Inconel 617 at 1000 °C	[41]
CrAl	ZhS6U	Cr alloying improves corrosion resistance and extends service life in aggressive combustion environments at 1100 °C after sea salt exposure	[42]
NiAl	nickel-based superalloy	Si-modified NiAl coating (8 wt.% Si/(Si + Al), 9.0 at.% Si) exhibited the best oxidation resistance at 1000 °C for 500 h	[43]
NiAl + $Al_{13}Cr_4Si_4$ and W_5Si_3	DS200 + Hf	addition of Si improves Type I corrosion resistance in Na_2SO_4 at 1000 °C for 24 h	[44]
Ni_3Al, NiAl, Ni_2Al_3	Pure nickel	Si-modified coating showed excellent resistance with no visible attack after 300 h at 700 °C.	[45]
NiAl	high-purity nickel	Improved sulphidation resistance via protective α-Al_2O_3 at 700 °C in air + 0.5% SO_2/SO_3, with limited effectiveness after incubation in solid Na_2SO_4	[46]

Slurry coatings enhance surface hardness and wear resistance due to the presence of intermetallic phases such as NiAl and Cr-rich precipitates. These phases provide high hardness and good thermal stability, which are particularly beneficial for components exposed to combined wear and high-temperature conditions [41]. However, compared to CVD, the mechanical improvements are more dependent on coating composition and process optimization rather than process control. The most significant advantage of slurry aluminizing lies in high-temperature oxidation and corrosion resistance. The incorporation of elements such as Si and Cr leads to the formation of more stable and protective oxide scales. For instance, CrSiAl coatings on Rene-80 exhibit superior corrosion resistance compared to conventional aluminide coatings due to improved scale stability during thermal cycling [40]. One should stress that silicon plays a particularly critical role in enhancing oxidation resistance. Si-modified coatings reduce oxide growth rates, improve scale adherence, and significantly extend service life during long-term exposure (e.g., up to 500 h at 1000 °C) [43]. These coatings also show excellent resistance to Type I hot corrosion by stabilizing the protective alumina layer [44]. In terms of corrosion behaviour, slurry coatings provide strong resistance in sulphidizing and salt-rich environments. For example, Si-modified aluminide coatings show negligible degradation even after prolonged exposure at 700 °C, indicating excellent resistance to aggressive atmospheres [45]. However, their performance may be limited in environments with molten salts after long incubation periods, suggesting some constraints in extreme conditions [46].

3.4. Hybrid Methods

Advanced coating technologies offer the highest degree of control over mechanical performance and high-temperature behaviour, enabling tailored solutions for specific applications (Table 4).

Table 4. Progress in aluminide coatings on nickel alloys produced by different techniques [47–71].

Coating	Substrate Material	Manufacturing Technology	Main Advantages	Ref.
Ni-Al/Ni-Al-Ce	Ni-based single-crystal superalloy	LAHT	superior spallation resistance during cyclic oxidation at 1100 °C (50 min heating, 10 min air cooling) over 100 h	[47]
NiAl/NiAlZr/ NiAlHf/NiAlCr	René N5	magnetron sputtering	Zr improves corrosion resistance, while Hf enhances oxide scale anchoring a synergistic effect of Zr and Hf significantly enhances coating performance (at 900 °C)	[48]
NiAl + Ni_5Al_3 + $AlCr_2$	IN625	Reactive Air Aluminizing (RAA)	improved resistance to high-temperature oxidation (at 1000 °C for 100 h)	[49]
NiAl	Inconel 690	hot-dipping aluminizing/ plasma-assisted heat treatment	Cr_2O_3 precipitates at grain boundaries in plasma-treated samples suppress intergranular embrittlement, preserving ductility and toughness, with hardness varying between 412.1 and 945 HV0.5 across phases	[50]
(Ni, Pt)Al	DD6	magnetron sputtering (MS)	C6 coating (45.1Ni–8.3Pt–46.6Al at.%) showed superior corrosion resistance at 900 °C for 100 h in static air after Na_2SO_4/NaCl (75:25 wt%) pre-deposition	[51]
NiAl + Cr-rich precipitates	IN738LC	reactive air aluminizing	high-temperature coatings deposited at 1120 °C showed ~100× lower oxidation rates than those formed at 845 °C at 1000 °C for 100 h, with degradation mainly driven by inward Al diffusion, more severe in low-temperature coatings	[52]
Al_2O_3-modified Ni_2Al_3/Al_2O_3-free Ni_2Al_3	Ni substrate	electroplated Ni-Al_2O_3 and Ni films at 620 °C	the degradation of the coating was reduced after the addition of nano-Al_2O_3 particles; addition of the nano-Al_2O_3 particles can reduce the oxidation rate (from $Kp = 1.4 \times 10^{-12}\ g^2/cm^4 \times s$ without nanoparticles to $Kp = 1.3 \times 10^{-12}\ g^2/cm^4 \times s$) and increase the oxide adhesion of the aluminide coating (oxidation at 1000 °C for 20 h).	[53]
β-(Ni,Pt)Al	AM1	electro-deposited layer of Pt/low-activity chemical vapour deposition + topcoats made of YSZ (EB-PVD)	Heavy grit blasting (higher pressure, shorter duration) increased TBC spallation resistance by 50%, while P600-ground surfaces provided the best performance and extended thermal cycling lifetime at 1100 °C by a factor of 2.7 compared with the reference	[54]

Table 4. *Cont.*

Coating	Substrate Material	Manufacturing Technology	Main Advantages	Ref.
NiAl + Ni_2Al_3	DD98M	arc ion plating	ion irradiation improves the oxidation resistance (at 1000 °C for 10 h) of aluminide coatings	[55]
NiAl + Re precipitates	nickel-based superalloy	electroplating NiRe + arc ion plating Al	incorporating Re improves the stability of the β-NiAl phase during oxidation (up to 300 h at 1100 °C)	[56]
Zr-Ni_3Al	Inconel-718	DC cosputtering	The highest hardness and Young's modulus of ~9.2 and ~150.3 GPa, respectively, are observed for 30 W (DC power) Zr-Ni_3Al coatings; 1.51 at. % of Zr in Ni_3Al coatings has shown the best oxidation resistance properties (at 900, 1000, 1100 °C in 30 cycles oxidation (60 min heating/30 min cooling at RT)	[57]
NiAl	CMSX-4	Laser-based directed energy deposition	applying preheating can eliminate the cold cracking; the maximum hardness of the samples was observed in ST3 (preheating 800 °C, feeding speed 0.625v1, laser power 0.625p1) with 653 HV	[58]
NiAl	René N5	arc ion plating	coating showed a lower average oxidation rate (0.8570 mg/cm^2) than the substrate (1.0035 mg/cm^2) after 300 h at 1050 °C.	[59]
PtAl	Ni-based single-crystal superalloy	Pt electroplating + "above pack" aluminization VPA	enhanced the oxidation resistance (at 1100 °C); the fracture strain increases from 41.23% to 47.07% (at 1100 °C/100 MPa)	[60]
(Ni, Pt)Al	SX	Pt electroplating + gas phase aluminizing	Ru influences rumpling in Pt–Al-coated single-crystal superalloys during cyclic oxidation at 1100 °C, suppressing it after >200 cycles but intensifying it between 50 and 150 cycles	[61]
NiAl-Cr/NiAl-Ta/NiAl-Cr-Ta	Inconel 718	L-DED	increased hardness up to a maximum value of 773 HV for NiAl-Ta (14 at.% Ta), 661 HV for NiAl-Cr (34 at.% Cr) and even 907 HV for NiAl-Ta-Cr (14 at.% Ta, 7.5 at.% Cr)	[62]
(Ni, Pt) Al + YSZ	DD5		Zr further improves both cyclic oxidation resistance (at 1100 °C) and hot corrosion resistance (in mixed salt at 900 °C) of the (Ni, Pt) Al coating	[63]
(Ni, Pt) Al/ ξ–Pt–Al_2 + β–(Ni, Pt) Al)/ $PtAl_2$	nickel-based superalloy	LTHA	Pt–Al coatings improved the high-temperature cyclic oxidation resistance of nickel-based superalloy	[64]
PtAl + NiRe	Ni_3Al-based SC superalloy	Electroplated Pt + NiRe	improved the oxidation resistance; inhibition of crack propagation, contributing to a superior ductility of Re-modified PtAl (at RT and 1100 °C for 50, 100, and 200 h in static air)	[65]

Table 4. *Cont.*

Coating	Substrate Material	Manufacturing Technology	Main Advantages	Ref.
NiAl + $Cr_{23}C_6$	ZhS6U/ZhS32	Vacum carburizing	diffusion and microcrack barriers significantly enhance the lifetime and reliability of high-temperature gas turbine engines	[66]
AlSiY/AlSiNiB/AlNiY	VZhM4	ion-plasma deposition	high heat resistance at 1050 °C for 500 h, high (AlSiNiB/AlNiY) or satisfactory (AlSiY) resistance to cyclic sulphide–oxide corrosion in Na_2SO_4 + NaCl salts on the melt surface at 850 °C in the course of 30 1 h cycles followed by cooling to room temperature	[67]
PtAl/PtReAl	Ni_3Al-based superalloy	electroplating Ni–Re/Pt + gaseous phase aluminizing	significantly impaired the ultimate tensile strength of the superalloy by about 10% at RT improved the oxidation resistance and ductility of the superalloy (at 1100 °C)	[68]
(Ni,Pd)Al +Zr/Hf	MAR-M247	palladium electroplating/ zirconization-aluminization/ hafnization-aluminization	Pd + Zr co-doping improved oxidation resistance compared with Pd + Hf in aluminide coatings at 1100 °C for 500 h	[69]
$NiAl_3$, Ni_2Al_3, NiAl	Inconel 601	spark plasma sintering	improved oxidation resistance in high-temperature air (about 3 times lower mass increase after 5 cycles of oxidation at 1273 K for 72 ks)	[70]
NiAl	Rene 125	low-activity vapour phase aluminization	improved the thermomechanical fatigue life of the coated system (by prior thermal ageing) at 1100 °C	[71]

These methods can significantly enhance hardness, ductility, and crack resistance. For example, laser-based directed energy deposition (L-DED) produces coatings with high hardness (up to ~650–900 HV depending on composition), while also reducing defects such as cold cracking through process optimization [58,62]. Similarly, plasma-assisted treatments improve ductility and prevent intergranular embrittlement by introducing beneficial phases (e.g., Cr_2O_3 at grain boundaries) [50]. Additionally, high-temperature mechanical performance is further improved through alloying additions. Elements such as Re and Pt stabilize the β-NiAl phase, inhibit crack propagation, and enhance ductility at elevated temperatures [56,65]. However, trade-offs may occur, as some modifications can reduce room-temperature strength while improving high-temperature behaviour. On the other hand, advanced methods enable exceptional performance through precise compositional control. Reactive air aluminizing and magnetron sputtering produce coatings with significantly reduced oxidation rates, in some cases up to 100 times lower depending on deposition conditions [52]. Alloying with reactive elements such as Zr and Hf further enhances oxide scale adhesion and reduces spallation during thermal cycling [48]. Additionally, hybrid coatings (e.g., Pt-, Zr-, or Dy-modified systems) exhibit superior behaviour in aggressive environments, including molten salts and cyclic oxidation conditions [51,63]. Nanoparticle-reinforced coatings (e.g., Al_2O_3 additions) further improve oxide adherence and reduce degradation kinetics [53].

3.5. Microstructural Aspects of Aluminide Coating Deposition

One should highlight that the literature also focuses on obtaining tailored microstructures only as this can further benefit in potential improvement in mechanical properties. Table 5 highlights that the manufacturing technology of aluminide coatings plays a decisive role in microstructure evolution, which directly governs both mechanical performance and high-temperature behaviour, including oxidation and corrosion resistance.

Table 5. Advances in tailored microstructures of aluminide coatings for Ni-based alloys [72–95].

Coating	Substrate Material	Manufacturing Technology	Main Advantages	Ref.
NiAl	MAR-M247	CVD	β-NiAl degradation in aluminide coatings is governed by Ni–Al interdiffusion and occurs at the surface and interface via heterogeneous nucleation	[72]
NiAl	MAR-M247	CVD	Reducing Ni content to 32% led to complete transformation into an inner aluminide layer of β-NiAl, σ, μ, and MC carbides, while 38–55% Ni resulted in sequential precipitation of μ, β-NiAl, and σ phases	[73]
NiAl	DZ411	CVD	Co–Al coatings with β-NiAl-like microstructure were formed on both inner and outer turbine blade surfaces, while heat treatment reduced coating thickness and increased oxidation	[74]
NiAl + $Cr_3(Ni, Co)_2$	K452	CVD	Whisker formation in the substrate diffusion zone occurred only at low deposition temperatures (850–950 °C), whereas at 1050 °C TCP phases transformed into stable Cr-rich carbides and Co dissolved into β-NiAl	[75]
NiAl	MAR-M247	CVD	Higher deposition temperatures progressively increased the thickness of the β-NiAl and interdiffusion layers	[76]
NiAl	MAR-M247	pack cementation/CVD	amount of activator and pure aluminum had a noticeable effect on the total thickness of obtained layers	[77]
(Ni, Pt) Al/YSZ bond coat	nickel base single crystal superalloy	CVD	Suppressing brittle $PtAl_2$ formation, enhancing TGO/bond coat interfacial toughness, and lowering TGO stress–strain levels are key to extending the thermal cycling life of (Ni,Pt)Al/YSZ TBCs	[78]
NiAl	K444	CVD	Aluminide coating on K444 shows a bilayer structure, with thickness controlled by deposition conditions and growth dominated by grain boundary diffusion	[79]

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Table 5. *Cont.*

Coating	Substrate Material	Manufacturing Technology	Main Advantages	Ref.
β-NiAl	IN792	low-activity and high-activity vapour phase aluminizing	<35 g powder produced LAHT aluminide coatings with a double-layer structure and precipitate-free outer zone due to Ni outward diffusion, while 100 g yielded a triple-layer coating with upper-layer precipitates indicating inward Al diffusion	[80]
NiAl	nickel	plasma spraying and alkaline etching	In situ NiO formation enhanced hydrogen evolution reaction (HER) activity, while the coexistence of NiO and $Ni_{0.58}Al_{0.42}$ improved reaction kinetics and mechanical durability	[81]
fcc-Ni phase + NiAl	René N5	electroless nickel pre-deposition followed by slurry aluminizing	Electroless Ni enables precipitate-free aluminide coatings, while slurry aluminizing yields low-activity, low-porosity structures	[82]
NiAl + Cr + $AlCr_2$	Inconel 718	slurry aluminizing	Coating phases act as diffusion barriers, limiting precipitation in the second reaction zone even after 150 thermal cycles at 1100 °C	[83]
Al_4C_3-NiCrAlY	Al_4C_3-NiCrAlY	spray drying and sintering	Stable composition and microstructure were maintained up to 1300 °C, with no notable phase interactions below 1250 °C	[84]
Al + metastable Ni_2Al_9	CrNi50WMoTiAlNb	hot dip aluminizing	melt-dipping enables the formation of a continuous aluminide coating on the $CrNi_{50}$WMoTiAlNb alloy surface	[85]
ζ-$PtAl_2$ + β-(Ni,Pt)Al	single-crystal nickel-based superalloys	slurry aluminizing	The process enabled formation of Pt-modified aluminides with a dual-phase ζ-$PtAl_2$/β-(Ni,Pt)Al microstructure, providing enhanced high-temperature oxidation and corrosion resistance	[86]
TBC system is yttria (Y_2O_3) partially stabilized zirconia (ZrO_2), YPSZ, ceramic EB-PVD top coat and (Ni,Pt)Al	AM1	APVS	Pre-defects introduced via LASDAM enable in situ monitoring of temperature and damage evolution, while faster cooling increases damage compared with slow cooling	[87]
NiAl + CoAl	IN738LC	pre-Co-electroplating + slurry aluminizing	Cobalt electroplating from Watts solution on IN738LC produced an adherent Co layer, while subsequent slurry aluminizing revealed a critical ~10 μm thickness for forming a low-activity Co-modified aluminide coating	[88]
$Al_{14}Cr_3Ni_2$ + Al_3Ni_2	Haynes 263	pack cementation (PC) aluminizing	REE additions in pack cementation for Ni superalloys (e.g., Yb) tend to segregate at the coating surface	[89]

Table 5. *Cont.*

Coating	Substrate Material	Manufacturing Technology	Main Advantages	Ref.
NiAl-Ru	nickel-based single crystal superalloy with high Mo (up to 11 wt.%) and low Re (max 1.8 wt.%) contents	Diffusion treatment is conducted at 1150 °C in argon atmosphere	Ru reduces interdiffusion layer thickness and modifies phase structure; in γ'-Ni_3Al, it suppresses Ni diffusion by increasing activation energy	[90]
Pt-Al	DD413	Pt electro-depositing + vapour phase aluminizing	with increasing thermal exposure time, MC carbides and σ-TCP phases partially dissolve in the interdiffusion zone (IDZ), while $M_{23}C_6$ carbides form at the interface; simultaneously, the SRZ and σ-TCP regions grow, and γ' precipitates in the substrate spheroidize and form raft-like structures	[91]
$CrAl_7$	EP718	hot-dip aluminizing	the two-layer coating consists of a CrAl7 solid solution and an Al matrix containing CrAl7 aluminide inclusions	[92]
NiAl and Cr-rich precipitates	IN738LC	Slurry RAA	The RAA method was successfully integrated into the standard heat treatment of IN738L, producing defect-free coatings without cracks, spallation, or uncoated areas	[93]
Ni-Al, Ni-Cr-Al, Ni-Cr-Fe-Al			the scratch hardness of 800 MPa.	[94]
Graded NiAl/ZR	Ni matrix, Cr 3.25, Al 21.87, Co 0.81, Fe 0.16, Mo 0.76, W 0.36, and Si 0.29	Spark Plasma Sintering	VKNA + 30% YSZ interlayer showed good heat resistance over 180 cycles at 1100 °C, with a crack fraction about 15 times lower than that of the 15% YSZ case.	[95]

A fundamental aspect revealed across multiple studies is that interdiffusion between coating and substrate controls microstructural stability and long-term performance. In CVD coatings on MAR-M247, degradation of the β-NiAl phase is driven by Ni–Al interdiffusion, leading to phase transformations and coating weakening over time [72]. This directly affects mechanical integrity, as phase instability promotes crack initiation and reduces fatigue resistance during long-term service. Additionally, changes in substrate composition (e.g., Ni content) significantly alter phase formation, leading to precipitation of brittle σ and μ phases, which can degrade ductility and toughness [73]. The coating architecture (layer thickness and phase distribution) is another critical factor controlled by processing technology. For instance, CVD coatings typically form a bilayer structure (outer β-NiAl + interdiffusion zone), with thickness strongly dependent on deposition temperature and time [79]. Increasing deposition temperature results in thicker coatings and interdiffusion layers, which can enhance oxidation resistance by providing a higher aluminum content, but may simultaneously reduce mechanical performance due to increased brittleness and residual stresses [76]. On the other hand, the formation of a continuous β-NiAl phase promotes the development of a stable α-Al_2O_3 scale, which is crucial for long-term oxidation resistance. However, microstructural defects such as grain boundary precipitates or TCP phases (e.g., in coatings deposited at lower temperatures) can act as fast diffusion paths, accelerating degradation [75]. In contrast, higher deposition temperatures promote transformation into more stable carbides and reduce detrimental phases, improving oxidation resistance.

The role of manufacturing parameters in controlling diffusion mechanisms is further illustrated in vapour phase aluminizing processes. Depending on activity (low vs. high), coatings can exhibit different microstructures (double-layer vs. triple-layer), indicating outward or inward diffusion dominance [80]. These differences strongly influence both mechanical and environmental performance, as diffusion-controlled growth determines coating adherence, porosity, and resistance to spallation. In slurry and hybrid processes, microstructure tailoring enables improved corrosion resistance and mechanical durability. For example, controlled phase formation (e.g., β-(Ni,Pt)Al + ζ-$PtAl_2$) leads to enhanced oxidation and corrosion resistance due to optimized phase distribution and improved oxide adhesion [86]. Similarly, the presence of Cr-rich or multi-phase structures in slurry coatings acts as diffusion barriers, limiting degradation even after prolonged thermal cycling [83]. Another important aspect is the reduction in porosity and defects through process optimization. Techniques such as electroless nickel pre-deposition followed by slurry aluminizing produce coatings with minimal porosity and controlled microstructure, improving both mechanical strength and oxidation resistance [82]. Reduced porosity limits crack initiation sites and prevents rapid ingress of oxygen or corrosive species. Advanced alloying additions and process modifications further enhance performance. For instance, Ru addition reduces interdiffusion layer thickness and slows diffusion kinetics, stabilizing the coating microstructure and improving long-term durability [90]. Similarly, controlling carbide precipitation and phase evolution in the interdiffusion zone affects creep resistance and high-temperature mechanical stability. Finally, microstructural stability also influences coating–substrate interaction under service conditions. The evolution of γ' precipitates, carbide dissolution, and TCP phase growth beneath the coating (e.g., in Pt-modified systems) can significantly affect substrate strength and creep resistance during long-term exposure [91]. This demonstrates that coating technology must be optimized not only for surface protection but also for maintaining substrate mechanical integrity.

The tailored microstructure of aluminide coating may be obtained by various methods, among which slurry aluminizing could be considered as effective ones. To further demonstrate the flexibility of the optimized slurry aluminizing process, platinum-modified aluminide coatings were produced [82], showing that modification of the aluminizing step can be used to tailor the resulting microstructure (Figure 3). A 4.5 μm Pt layer was deposited on the superalloy substrate, followed by a pre-aluminizing diffusion heat treatment prior to slurry application. The resulting Pt–aluminide coating (Figure 3a) had a total thickness of 98 ± 4 μm, including a 24 ± 3 μm interdiffusion zone and a 29 ± 3 μm outer biphasic layer. As shown in Figure 3b, the outer layer consists of ζ-$PtAl_2$ and β-(Ni,Pt)Al, with phase distribution and composition governed by the aluminizing conditions. Fine Ta- and W-rich precipitates are also observed, mainly along grain boundaries, originating from the substrate. These results confirm that adjusting aluminizing parameters enables control over the coating's phase constitution and microstructure.

Table 6 provides a systematic comparison of the main aluminide coating technologies, highlighting that their performance cannot be evaluated based on a single parameter. While all methods improve oxidation resistance through the formation of protective α-Al_2O_3 scales, significant differences may be observed when mechanical performance, coating thickness, and process characteristics are considered simultaneously. CVD coatings offer the most balanced performance due to their controlled microstructure and moderate thickness, enabling a favourable combination of oxidation resistance and fatigue behaviour. In contrast, pack cementation produces thicker coatings with a higher aluminum content, which enhances long-term oxidation resistance but introduces brittleness and reduces fatigue life due to increased stiffness and residual stresses. Slurry aluminizing represents a more flexible approach, where compositional modifications (e.g., Si, Cr) improve corrosion and oxidation resistance; however, the resulting mechanical properties are more sensitive to processing conditions. Advanced and hybrid techniques provide the highest degree of property tailoring, enabling simultaneous improvements in oxidation resistance and mechanical performance, although their industrial application is currently limited by complexity and scalability.

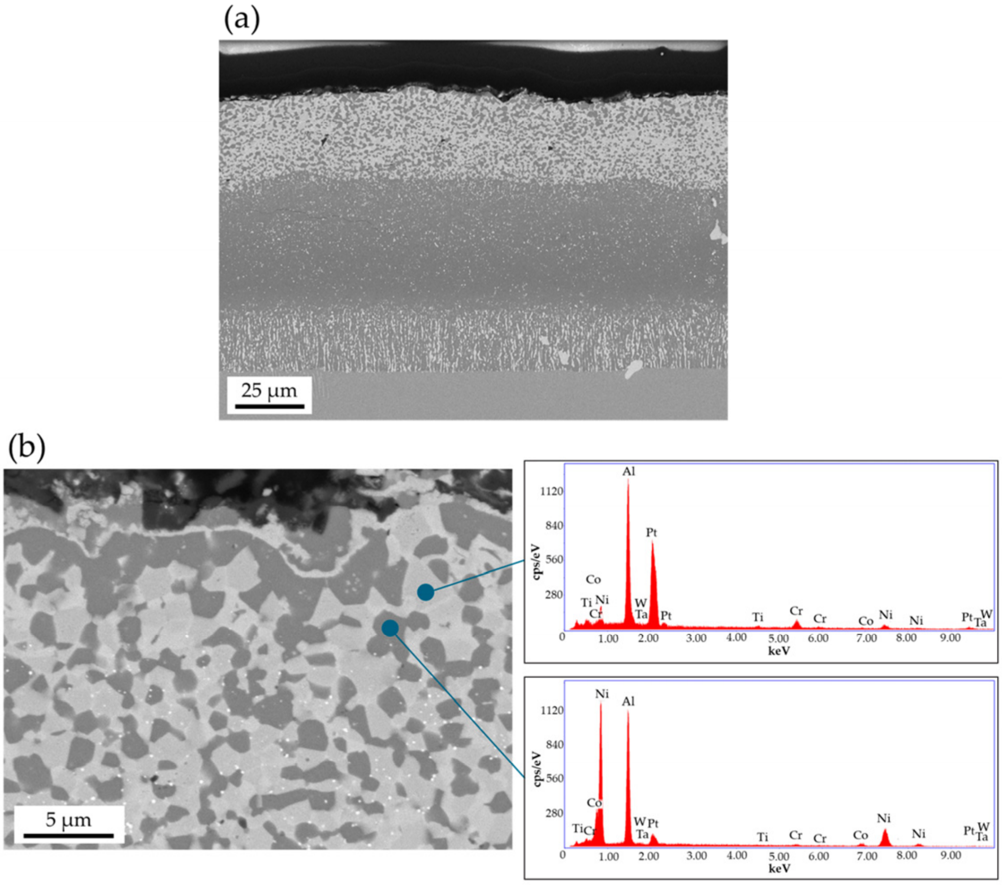

Figure 3. Pt–aluminide coating cross-section fabricated by optimized slurry route (**a**); high-resolution micrograph of outer biphasic region with elemental analysis (**b**) [82].

Table 6. Comparative analysis of aluminide coating deposition techniques for Ni-based superalloys.

Deposition Method	Oxidation Resistance	Mechanical Performance	Typical Coating Thickness	Key Advantages	Main Limitations	Critical Trade-Offs
CVD	Excellent (stable α-Al_2O_3, slow kinetics)	Very good (good fatigue, controlled microstructure)	Thin–moderate (~15–40 µm)	High uniformity, strong adhesion, precise control of diffusion	High cost, complex processing	Balance between oxidation resistance and fatigue; thinner coatings improve fatigue but reduce Al reservoir
Pack cementation	Excellent (large Al reservoir, long-term protection)	Moderate (high hardness but reduced ductility/fatigue)	Thick (~50–200 µm)	Simple, cost-effective, widely used industrially	Brittle phases, residual stresses, less control over microstructure	Improved oxidation vs. reduced fatigue resistance and increased brittleness

Table 6. *Cont.*

Deposition Method	Oxidation Resistance	Mechanical Performance	Typical Coating Thickness	Key Advantages	Main Limitations	Critical Trade-Offs
Slurry aluminizing	Very good (enhanced by Si/Cr additions)	Moderate–good (composition-dependent)	Moderate (~30–100 µm)	High flexibility, compositional tailoring, relatively low cost	Less uniform coatings, process sensitivity	Enhanced corrosion/oxidation vs. variability in mechanical performance
Hybrid/advanced methods	Excellent to superior (tailored compositions, reduced oxidation rates)	Excellent (can optimize hardness, ductility, crack resistance)	Variable (process-dependent)	Maximum property control, multifunctional optimization	High complexity, limited scalability, cost	Superior performance vs. limited industrial applicability and reproducibility

4. Discussion

4.1. Microstructural Concerns Raised During Aluminide Coating Deposition

One should highlight that although all aluminizing techniques lead to the formation of β-NiAl-based protective layers, the underlying mechanisms responsible for phase formation, stability, and degradation differ significantly depending on the deposition technique. These differences arise primarily from variations in aluminum activity, diffusion kinetics, and thermodynamic conditions during coating growth, which ultimately control the microstructural evolution and long-term performance of the coatings. In the case of CVD, coating formation is governed by controlled gas-phase reactions and relatively low aluminum activity, promoting a diffusion-limited growth mechanism dominated by inward aluminum diffusion and outward nickel transport [2]. This results in a well-defined bilayer structure consisting of an outer β-NiAl layer and a relatively thin interdiffusion zone [15]. The controlled kinetics and high process uniformity favour the formation of a chemically homogeneous β-NiAl phase with reduced defect density, which contributes to improved phase stability during high-temperature exposure [16]. However, long-term degradation is still driven by gradual Ni–Al interdiffusion, leading to β-phase depletion and the potential formation of secondary phases [72,73]. In contrast, pack cementation typically operates under higher aluminum activity conditions, which promotes rapid coating growth and often leads to the formation of multiphase structures, including β-NiAl and Ni_2Al_3 [30,35]. The dominant diffusion mechanism shifts toward outward diffusion of nickel, resulting in thicker coatings and more pronounced interdiffusion zones [80]. While this provides a higher aluminum content and enhances oxidation resistance [31,38], it also introduces higher residual stresses and increased susceptibility to brittleness and phase instability during thermal exposure [30]. The presence of multiphase regions can further accelerate degradation through preferential diffusion paths and phase transformations. These differences are also reflected in slurry aluminizing and hybrid processes, where the balance between diffusion control and compositional tailoring determines phase constitution and stability. Slurry methods, for example, enable localized compositional modification (e.g., Si or Cr additions), which can stabilize the β-NiAl phase indirectly by improving oxide scale adherence and reducing diffusion rates [40,43]. Advanced hybrid techniques further modify these mechanisms by introducing alloying elements (e.g., Pt, Re, Hf) that reduce interdiffusion kinetics and enhance β-phase stability under prolonged exposure [56,65,90]. Therefore, while similar improvements in hardness, oxidation resistance, and corrosion behaviour are frequently reported across different techniques, these properties originate from fundamentally different microstructural and diffusion-controlled mechanisms.

https://doi.org/10.3390/coatings16040506

An important aspect that must be considered, particularly in the context of emerging manufacturing technologies, is the influence of microstructural heterogeneity in AM substrates on coating formation and performance. Unlike conventionally processed alloys, AM materials often exhibit pronounced anisotropy, including columnar grain structures aligned with the build direction, chemical segregation, and spatial variations in phase distribution. These features have a direct impact on aluminide coating growth. Diffusion-controlled processes such as CVD or pack cementation are highly sensitive to local microstructure. Therefore, variations in grain size and crystallographic orientation can lead to non-uniform diffusion rates of Ni and Al [72,79]. As a result, coatings formed on AM substrates may exhibit variations in thickness, phase composition, and interdiffusion zone development depending on the build direction and local microstructural characteristics. Furthermore, microsegregation inherent to AM processing can locally alter thermodynamic driving forces for phase formation, promoting heterogeneous nucleation of β-NiAl or secondary phases [73,80]. This may result in non-uniform coating, which can affect both oxidation resistance and mechanical performance. For example, regions with finer grains may enhance diffusion and promote more uniform coating growth, whereas coarse columnar grains may lead to localized thickening or depletion zones [75]. Such heterogeneity also has implications for mechanical reliability. Variations in coating thickness and interfacial properties can introduce localized stress concentrations under thermomechanical loading, potentially accelerating crack initiation and reducing fatigue life [13,19]. Therefore, achieving uniform and reliable coating performance on AM substrates requires careful consideration of the initial microstructure, and in some cases, the application of post-processing treatments (e.g., heat treatment or surface homogenization) prior to aluminizing.

4.2. Statistical Analysis of Current Trends in Aluminide Coatings for Nickel-Based Alloys

The quantitative trends presented in Figures 4–6 provide important insight into how research priorities in aluminide coatings are distributed across substrate materials, manufacturing technologies, and targeted performance improvements. When interpreted together, these figures reveal that the number of publications is not random, but strongly reflects industrial relevance, technological maturity, and the complexity of performance challenges. The higher number of publications for substrates such as MAR-M247, Inconel 718, and Inconel 625 directly correlates with their widespread industrial application and sensitivity to high-temperature degradation. The number of studies on MAR-M247 is particularly significant, where CVD coatings are extensively investigated for fatigue and oxidation performance [13,19,20,22]. The large number of papers indicates that this alloy serves as a main material for evaluating coating-induced improvements in both mechanical and environmental resistance. Similarly, the high publication count for Inconel 718 reflects its complex chemistry and industrial importance. Numerous studies (Tables 1, 2 and 4) focus on its oxidation and corrosion behaviour, particularly the beneficial role of Fe in promoting α-Al_2O_3 formation and improving coating performance [18,25]. The diversity of coating methods applied to this alloy explains its strong representation in the literature. For Inconel 625, the relatively high number of studies is linked to its use in additive manufacturing and harsh environments. As shown in Table 2, pack cementation significantly enhances its hardness and oxidation resistance [30,35], which explains why it is frequently selected for evaluating mechanical strengthening effects.

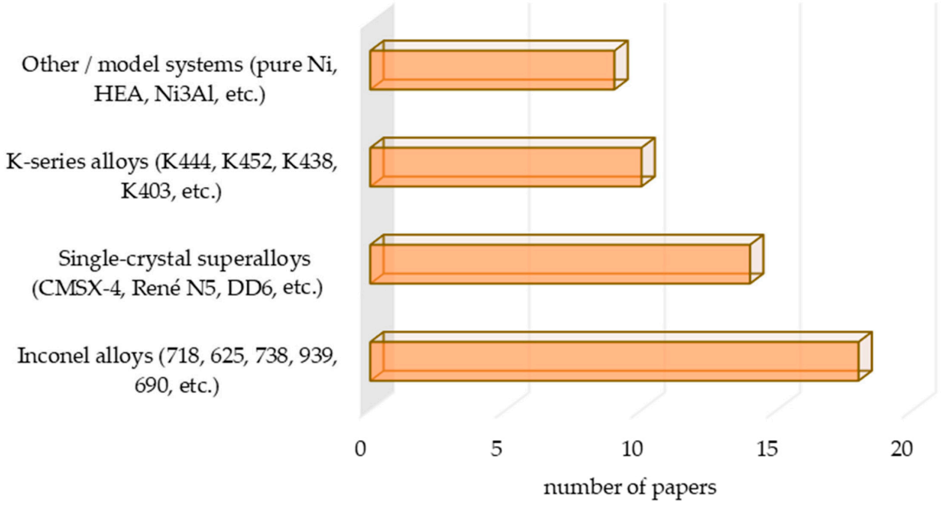

Figure 4. Comparison of the number of papers related to specific substrate material.

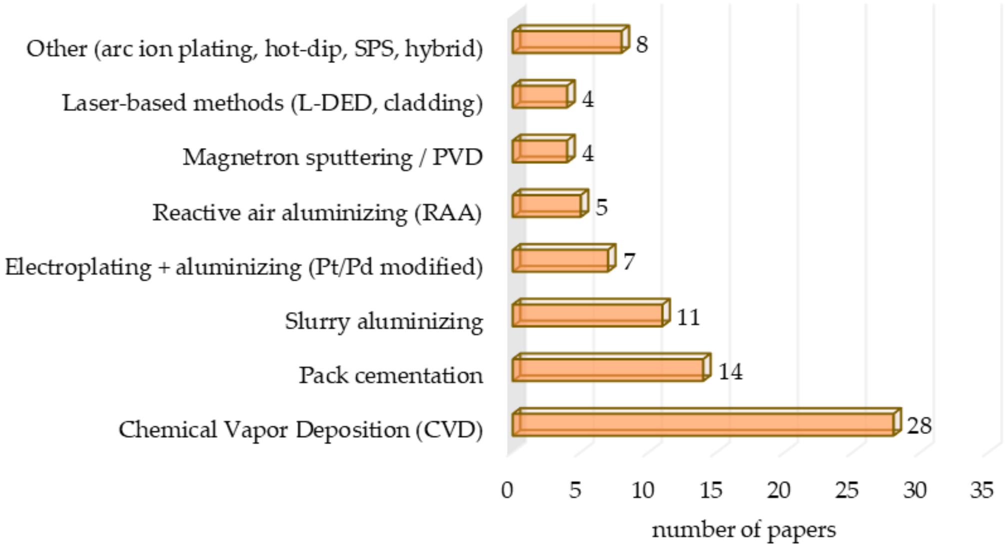

Figure 5. Comparison of the number of papers related to specific manufacturing technology of aluminide coatings for nickel-based alloys.

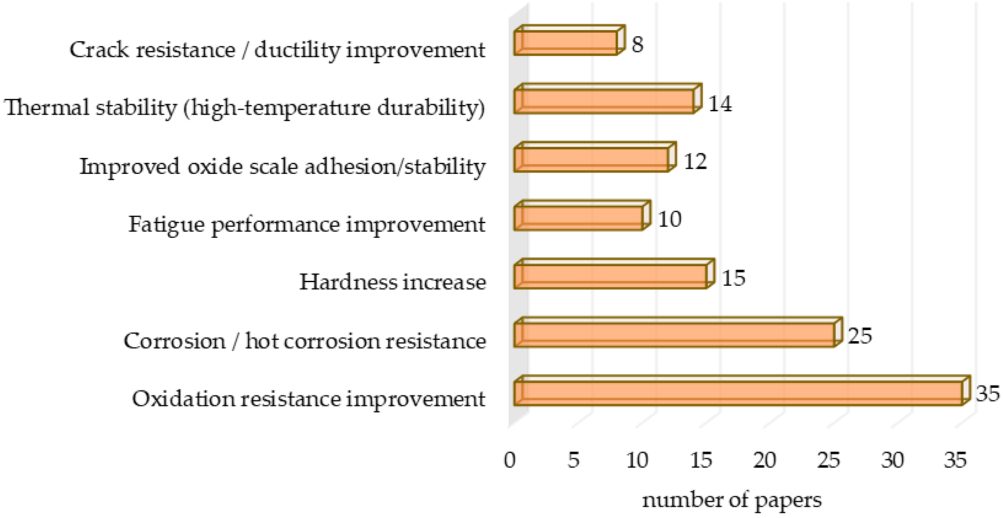

Figure 6. Comparison of number of papers related to improvement in specific properties of coated materials.

The high number of papers on CVD shown in Figure 5 is consistent with the large number of entries in Table 1, confirming that it is the most extensively studied coating technology. This high publication number reflects its ability to simultaneously improve hardness [10], fatigue life [11], and oxidation resistance [15], making it the most versatile and industrially relevant method. The number of studies on CVD confirm that coating–substrate interactions and microstructural evolutions are critical for long-term performance; therefore, they are investigated in detail. Pack cementation, with the second-highest number of publications, reflects its industrial practicality and cost-effectiveness. In Table 2, pack cementation shows consistent improvements in oxidation resistance and hardness across multiple alloys [30,31,35], explaining why it remains a widely researched method despite its lower microstructural precision compared to CVD. The high number of studies suggests that pack cementation is often used as a baseline or reference technology. Slurry aluminizing, although represented by fewer publications, shows a growing research interest due to its flexibility in compositional design. As seen in Table 3, the addition of Si and Cr significantly improves corrosion resistance and oxide stability [40,43]. The moderate number of papers reflects its emerging role as a customizable and cost-effective alternative. Other advanced methods such as magnetron sputtering, reactive air aluminizing, and laser-based deposition correspond to Table 4. Their relatively low publication count indicates that they are still developing technologies, despite offering superior property tailoring. For example, significant improvements in oxidation resistance (up to 100× reduction in oxidation rate) [52] and hardness enhancement [62] highlight their potential, but the limited number of studies suggests higher complexity and lower industrial maturity.

Figure 6 clearly shows that oxidation resistance dominates the research interest, which is consistent with the majority of results presented across all tables. The large number of studies focusing on oxidation is supported by extensive data from CVD (Table 1), pack cementation (Table 2), and slurry processes (Table 3), all demonstrating significant reductions in oxidation rates through α-Al_2O_3 formation [15,31,43]. The dominance of this category reflects the primary role of aluminide coatings in protecting components in high-temperature oxidative environments. Corrosion resistance is the second most studied property, with a substantial number of publications. This is particularly evident in studies involving aggressive environments (NaCl, Na_2SO_4), where both CVD and slurry coatings show strong improvements [12,24,44]. The slightly lower number of papers compared to oxidation suggests that corrosion is often studied as a secondary but critical degradation mechanism, especially in marine or combustion environments. While aluminide coatings are widely reported to improve oxidation and corrosion resistance, it is important to mention that these benefits are often accompanied by performance trade-offs. A more balanced assessment reveals that coating design requires careful optimization to avoid adverse effects on mechanical integrity and long-term stability. One of the most significant trade-offs concerns coating thickness. Although thicker coatings provide a higher aluminum content and improve oxidation resistance, they can negatively affect fatigue performance due to increased stiffness, residual stresses, and stress concentration at the coating–substrate interface. For example, it has been shown that reducing coating thickness from ~40 μm to ~20 μm can significantly improve fatigue life under cyclic loading conditions [13]. This demonstrates that maximizing oxidation resistance does not necessarily lead to optimal mechanical performance. Similarly, the formation of multiphase coatings, particularly in high-activity processes such as pack cementation, can result in increased hardness but also enhanced brittleness. The presence of phases such as Ni_2Al_3, while beneficial for hardness, may reduce ductility and promote crack initiation under mechanical or thermomechanical loading. Another important limitation arises from interdiffusion processes during high-temperature exposure. Although diffusion is essential for coating formation, prolonged service leads to depletion of the β-NiAl phase and the growth of the interdiffusion zone, which can degrade both oxidation resistance and mechanical properties over time [72]. This effect is particularly critical in long-term applications, where phase instability may lead to the formation of brittle secondary phases. Furthermore, alloying additions used to enhance oxidation resistance—such as Pt, Re, or reactive elements—can introduce additional trade-offs. While these elements improve oxide scale adhesion and slow degradation kinetics, they may also increase cost, alter mechanical behaviour, or, in some cases, reduce room-temperature strength [56,68].

Mechanical performance (hardness, fatigue, wear) shows a comparatively lower number of publications, which is consistent with Figure 6 and the data in Tables 1–4. While significant improvements are reported—such as hardness doubling in CVD coatings [10] or substantial strengthening in pack cementation [30]—these aspects are less frequently investigated. However, the presence of multiple fatigue-related studies on MAR-M247 [13,19] indicates a growing recognition of the importance of mechanical integrity in coated systems, especially under cyclic loading conditions.

Notably, the smaller but increasing number of studies addressing combined properties (oxidation and mechanical performance) suggests a shift toward multi-functional optimization, particularly in advanced coating technologies (Table 4), where simultaneous improvements in hardness, oxidation resistance, and ductility are achieved [52,60,62].

When the publication data from Figures 4–6 are considered collectively, several important trends become evident. Higher numbers of studies are consistently associated with industrially critical materials and well-established coating technologies, such as MAR-M247 and chemical vapour deposition (CVD), reflecting their frequent use and practical importance in real-world applications. Across the literature, oxidation resistance clearly dominates the research focus, as it represents the primary degradation mechanism in high-temperature environments. In contrast, mechanical performance—particularly properties such as fatigue resistance—is comparatively underrepresented, although it is gaining increasing attention due to its importance in structural reliability. At the same time, emerging coating technologies are characterized by a smaller number of publications but demonstrate disproportionately significant improvements in performance, highlighting their strong potential for future development. One should note that the distribution of publications not only indicates current research priorities but also illustrates a clear shift in the field, moving from predominantly oxidation-focused studies on conventional systems toward more integrated approaches that aim to optimize multiple properties through advanced coating technologies.

It should be emphasized that the distributions presented in Figures 4–6 are based on a curated dataset of 95 publications and, therefore, should be interpreted with caution. The observed trends can be interpreted in a semi-quantitative manner. The higher number of publications associated with specific substrates (e.g., MAR-M247, Inconel 718) and technologies (e.g., CVD) is strongly linked to their industrial relevance, availability, and well-established processing techniques. In contrast, the lower publication number of advanced or hybrid techniques likely reflects their emerging status, higher processing complexity, and limited industrial adoption rather than a lack of scientific interest. Furthermore, it is important to consider the potential influence of publication bias. Research demonstrating significant improvements in oxidation resistance or mechanical performance is more likely to be published, which may lead to overrepresentation of successful coating systems and underrepresentation of negative or inconclusive results. Similarly, widely used materials and conventional technologies are more frequently studied, reinforcing their dominance in the literature. Therefore, the distributions shown in Figures 4–6 should be understood as indicators of research activity and technological maturity rather than definitive measures of scientific importance or performance superiority.

One should note that the distribution of research efforts is driven by the underlying thermodynamic and kinetic mechanisms controlling aluminide coating performance. The clear predominance of oxidation-related studies can be directly attributed to the diffusion-controlled nature of high-temperature degradation. The effectiveness of aluminide coatings is primarily determined by their ability to form and maintain a continuous, slow-growing α-Al_2O_3 scale, the stability of which depends on aluminum chemical activity, the integrity of the β-NiAl phase, and interdiffusion processes at the coating–substrate interface [5–7,72]. Consequently, a substantial portion of the literature focuses on maximizing aluminum availability and minimizing scale spallation through compositional design (e.g., Pt, Y, Hf additions) and optimization of deposition parameters [10,12,24]. The high share of CVD and pack cementation works in Figure 5 can be further explained by their distinct diffusion mechanisms and resulting microstructural characteristics. CVD coatings are typically formed under low aluminum activity conditions, leading to diffusion-controlled growth dominated by inward aluminum flux and outward nickel transport, which results in a relatively thin, uniform β-NiAl layer with a well-defined interdiffusion zone [15,79]. This controlled microstructure enhances phase stability and reduces defect density, which is beneficial for both oxidation resistance and fatigue performance [11,13]. In contrast, pack cementation operates under higher aluminum activity, promoting rapid coating growth and the formation of thicker, often multiphase layers (e.g., β-NiAl + Ni_2Al_3), which provide a larger aluminum reservoir and superior long-term oxidation resistance [30,31]. However, these microstructural features also introduce higher residual stresses, increased brittleness, and a greater susceptibility to crack initiation, particularly under cyclic loading conditions [30,35]. The comparatively lower representation of mechanical performance in Figure 6 reflects the inherent complexity of deformation and damage mechanisms in coated systems. Unlike oxidation, which is primarily governed by diffusion and thermodynamics, mechanical behaviour is controlled by a combination of factors, including coating thickness, elastic mismatch, residual stress evolution, and interfacial integrity [13,19]. For example, while thicker coatings improve oxidation resistance by extending aluminum supply, they simultaneously increase stiffness and stress concentration at the coating–substrate interface, thereby reducing fatigue life [13]. Furthermore, long-term exposure leads to progressive β-NiAl depletion and growth of the interdiffusion zone, accompanied by the formation of brittle secondary phases such as TCP phases, which degrade both ductility and creep resistance [72,73]. These competing effects make it difficult to simultaneously optimize mechanical and environmental performance, explaining why multifunctional studies remain relatively limited.

From a practical standpoint, the trends observed in Figures 4–6 closely reflect industrial requirements and technological maturity. The concentration of studies on alloys such as MAR-M247, Inconel 718, and Inconel 625 is directly linked to their widespread application in turbine and aerospace components, where oxidation and hot corrosion are the primary life-limiting factors [2,18,30]. The dominance of CVD in the literature is consistent with its industrial relevance, as it provides high coating uniformity, reproducibility, and compatibility with complex geometries, which are critical for high-value components such as turbine blades [10,15]. Conversely, the relatively limited number of studies on advanced and hybrid techniques, despite their demonstrated ability to significantly reduce oxidation rates and enhance mechanical performance [52,62], indicates that their adoption is currently constrained by processing complexity, cost, and scalability. Importantly, the increasing number of studies focusing on compositionally modified and hybrid coatings suggests a transition from single-property optimization toward multifunctional design. This shift is particularly evident in approaches that combine reactive element additions with advanced deposition techniques to simultaneously improve oxide scale adhesion, suppress interdiffusion, and enhance mechanical stability [48,56,65]. Such strategies directly address the fundamental limitation of conventional aluminide coatings, namely the trade-off between oxidation resistance and mechanical integrity.

5. Conclusions

This review provides a comprehensive and critically comparative analysis of aluminide coatings for nickel-based superalloys, demonstrating that their performance is governed not only by composition but primarily by the interplay between deposition method, diffusion mechanisms, and resulting microstructural evolution. A key outcome of this work is the clear identification that coating performance cannot be evaluated in isolation based on oxidation resistance alone. Instead, each deposition technique establishes a distinct balance between environmental protection and mechanical integrity. CVD coatings provide the most consistent and balanced performance due to their controlled growth kinetics and uniform β-NiAl microstructure, enabling favourable oxidation resistance while maintaining relatively good fatigue behaviour. In contrast, pack cementation, despite offering superior long-term oxidation resistance through thicker coatings and a higher aluminum content, introduces fundamental limitations related to brittleness, residual stresses, and reduced resistance to cyclic loading. Slurry aluminizing emerges as a highly adaptable approach, where compositional modifications (e.g., Si, Cr) enable targeted improvements in corrosion resistance and oxide scale stability, though often at the expense of process sensitivity and less predictable mechanical response. Advanced and hybrid techniques represent the most promising direction, as they enable precise control of composition and microstructure, allowing simultaneous enhancement of oxidation resistance and mechanical performance; however, their industrial adoption remains constrained by complexity, cost, and scalability. Importantly, this review highlights that the fundamental limitation of current aluminide coatings lies in the inherent trade-offs imposed by diffusion-controlled processes. Increasing coating thickness or aluminum activity improves oxidation resistance but simultaneously promotes stiffness, residual stress accumulation, and crack initiation under thermomechanical loading. Likewise, long-term interdiffusion leads to β-NiAl depletion and the formation of secondary phases, which progressively degrade both environmental resistance and mechanical stability. These coupled degradation mechanisms demonstrate that achieving optimal performance requires not maximizing a single property, but carefully balancing competing factors within a given application context. The analysis of the recent literature further reveals a clear imbalance in research focus. While oxidation resistance remains the dominant topic, mechanical reliability—particularly fatigue and thermomechanical behaviour—remains comparatively underexplored, despite its critical importance for real-world applications. At the same time, the growing interest in hybrid and compositionally tailored coatings indicates a transition toward multifunctional design strategies aimed at overcoming the limitations of conventional approaches. From an application perspective, the results emphasize that no single deposition technique can be considered universally superior. Instead, the optimal coating solution must be selected based on specific service conditions, taking into account environmental resistance and mechanical loading, component geometry, and manufacturing constraints. This is particularly relevant for emerging technologies such as additive manufacturing, where substrate heterogeneity introduces additional complexity in coating formation and performance. Future progress in the field will depend on advancing beyond traditional diffusion-based optimization toward integrated design approaches that couple processing, microstructure, and performance. Key directions include the development of coatings with controlled interdiffusion behaviour, enhanced phase stability under long-term exposure, and improved compatibility with complex substrate microstructures. Ultimately, the design of next-generation aluminide coatings will require a shift from single-property optimization to truly multifunctional systems capable of sustaining both environmental and mechanical demands in increasingly extreme operating conditions.

Author Contributions: Conceptualisation, M.K.; methodology, K.P., M.K.; validation, M.K.; formal analysis K.P., M.K.; investigation, K.P., M.K.; resources, M.K.; data curation, K.P.; writing—original draft preparation, K.P., M.K.; writing—review and editing, M.K.; visualization, M.K.; supervision, M.K.; project administration, M.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: All data are available upon request. The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

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https://doi.org/10.3390/coatings16040506