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Review

Improvement of the High Temperature Wear Resistance of Laser Cladding Nickel-Based Coating: A Review

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Abstract: Nickel-based coatings obtained by laser melting are broadly applied for surface modification owing to their high bond strength and exceptional wear resistance. Nickel-based laser cladding coatings are also extensively employed in high temperature wear environments. In this paper, the research progress on improving the high temperature wear resistance of laser cladding nickel-based composite coatings was reviewed by introducing a hard ceramic phase, adding solid lubricants and rare earth elements. On this basis, the material system to enhance the high temperature wear resistance of coating was summarized from the perspectives of the type, addition amount, morphology and distribution law of the hard ceramic phase, etc. The synergistic effect of various lubricants on improving the high temperature wear resistance of coating was discussed, and the action mechanism of solid lubricants in the high temperature extreme environment was analyzed. Finally, this paper summarizes the main difficulties involved in increasing the high temperature wear resistance of nickel-based coatings and some problems worthy of attention in the future development.

Keywords: laser cladding; nickel-based coatings; high temperature wear resistance; hard ceramic phase; solid lubricants

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1. Introduction

Some instruments and equipment in aerospace, vehicles and ships, petrochemical and other fields have a harsh working environment. For example, turbine engine rotors for large engines, gas turbine blades, bearings, etc., need to be served in high temperature environments for a long time [1–4]. Wear of components poses a risk to the safe use of the equipment and also increases the production costs of companies. Therefore, promoting the abrasion resistance of materials in high temperature environments is an important challenge in the field of tribology [5,6]. In comparison with the conventional surface modification process, laser cladding exhibits the benefit of higher energy density and lower dilution rate, which enables effective refinement of the tissue and improvement of coating elemental segregation [7–9]. Nickel-based powder has favorable corrosion resistance and wettability, and the Cr elements in the melt pool will react with C and B elements to produce Cr_7C_3, $Cr_{23}C_6$, CrB and other phases during the preparation of the coating by laser cladding, which are capable of raising the microhardness and wear resistance of the coating [10,11]. However, as the temperature increases, the phase within the NiCrBSi coating starts to change. The γ-Ni grains within the coating grow gradually when the temperature increases to 480 °C. In accordance with Hall–Petch equation, it is well known that the hardness of the coating decreases as the grain size increases, which eventually leads to a decrease in the abrasion resistance of the coating [12,13]. At 600 °C, the hard ceramic phase Cr_7C_3, which has a high content in the NiCrBSi coating, starts to coarsen and the hardness of the coating decreases [14]. CrB precipitation can be observed in the γ-Ni substrate at 700 °C, and this reduces the solid solution strengthening effect of Cr in the substrate. The interplate polymerization force and toughness of the coating decrease, and the abrasion resistance of the coating deteriorates [15].

At present, domestic and foreign scholars have conducted a lot of research and explored a series of alloy systems around enhancing the wear resistance of Nickel-based composite coatings at room temperature [16–18]. However, few have collated the results of promoting the high temperature wear resistance of laser-cladding Nickel-based coatings. A review of the relevant literature reveals that the improvement of high temperature wear resistance of Nickel-based coatings is mainly through the addition of hard ceramic phases and lubricants. The addition of a hard ceramic phase is principally to maintain the high hardness of the coating under high temperature conditions and to avoid the coating from spalling in a large area during the abrasion process so that the coating has good high temperature wear resistance. Adding lubricants is another common method. The lower the coefficient of friction of a material, the better its wear resistance. The solid lubricant still has superior lubrication at high temperatures and raises the high temperature abrasion resistance of the coating by decreasing the friction coefficient of the coating.

2. Ceramic Phase

The wear resistance of a material is usually positively correlated with the hardness of the material, and the addition of hard ceramic phases to Nickel-based coatings can effectively boost the microhardness of the coating and thus, its wear resistance [19,20]. At room temperature, the wear resistance of coatings is usually improved by adding hard ceramic phases such as Cr_3C_2, B_4C, TiC, WC, and NbC [21–25]. However, due to the decomposition and transformation of most hard ceramic phases under high temperature conditions, the number and stability of hard ceramic phases in the coating decreases, resulting in a significant reduction in the wear resistance of the coating. After years of research and exploration, the current additive phases with better effects on improving the high temperature wear resistance of nickel-based coatings are WC and TaC.

2.1. WC

WC has a high melting point of 2600 °C and is stable at high temperatures. Table 1 summarizes the material systems, high temperature wear resistance test conditions and the key findings for the accession of WC to improve the high temperature wear resistance of laser cladding Ni-based coatings.

Professor Zhou's group at the Chinese Academy of Sciences investigated the influence of WC under the high temperature abrasion resistance of nickel-based coatings [26]. When comparing the abrasion of Nickel based coating and NiCrBSi/WC nickel-based composite coating at 500 °C during testing, it was found that the wear rate of the coating decreased significantly after the addition of WC. Experimentally, it is demonstrated that the addition of WC is effective in improving the high temperature abrasion resistance of nickel-based coatings. Notably, the COF (Coefficient of friction) of NiCrBSi/WC Nickel-based composite coating is higher and fluctuates significantly at each temperature. The authors suggest that this may be attributed to the non-uniform distribution of the hard ceramic phase of WC in the composite coating. The larger WC phase is dislodged to become abrasive particles during the frictional wear experiments and severe three-body wear occurs between the coating and the Si_3N_4 grinding balls, thus causing an increase in the COF. This phenomenon has also been observed in many papers [27–29]. In order to expand the applicability of titanium and titanium alloys, Guo et al. [30] prepared NiCrBSi and NiCrBSi/WC-Ni composite coatings over pure titanium plates to research the impact of WC on the high temperature abrasion resistance in Ni-based coatings. The results of frictional wear tests at 300 °C and 500 °C demonstrated that both kinds of coatings experienced slight abrasive and fatigue wear. In addition, due to the high hardness of WC, the abrasion ratio of Ni-based composite coating with WC addition is approximately 24–47 times higher than that of pure titanium matrix. The influence of various amounts of CeO2 additives on the high temperature wear resistance of NiCrBSi/WC coatings was studied further by Wang et al. [31]. NiCrBSi/WC coating wear mechanism under high temperature is adhesive wear and oxidation wear, while the additive of rare earth oxide changes the wear mechanism. Furthermore, 0.5% CeO_2 had the most obvious improvement in the wear resistance, at which time the wear mechanism of the coating surface was slightly abrasive wear.

Table 1. Test and key findings of adding WC to improve wear resistance of coating at high temperature.

Ref.	Substrate	Matrix	Ceramic Phase	Key Findings	Tribological Testing Process, Parameters
Zhou, 2011 [26]	1Cr18Ni 9Ti	NiCrBSi	WC	Coatings produced by supplementing WC powder with NiCrBSi display greater high temperature abrasion resistance than NiCrBSi coatings	A THT07-135 pin-on-disk tribometer; Si_3N_4 ball (diameter 6 mm); Load: 5 N; Temperature: 25, 500 °C; Sliding speed 300 mm/s; Sliding distance: 500 m
Guo, 2010 [30]	pure Ti discs	NiCrBSi	WC	Under similar circumstances, the abrasion rate of the NiCrBSi/WC-Ni composite coating is around 24–47 times lower than that of the pure Ti substrate	A THT07-135 pin-on-disk tribometer; Si_3N_4 ball (6 mm). Temperatures: 300 °C, 500 °C; Load: 5 N; Sliding speed: 300 mm/s; Sliding distance: 500 m
Wang, 2013 [31]	4Cr14Ni14NW2Mo	NiCrBSi	WC, CeO_2	Ni21 + 20%WC + 0.5%CeO_2 coating microstructure was effectively refined and the coating presented a relatively well-abrasive behavior	A MG-200 high speed and temperature wear test machine. Grinding ring: heat-resistant cast iron; Temperature: RT (Rome temperature), 250, 450 and 650 °C; Load: 300 N; Velocity: 25 r/s; Load time: 3~3.5 min

2.2. *TaC*

As a robust carbide-forming element under high temperatures, Ta is an attractive additive for enhancing the high temperature wear resistance of coatings as it is very easy to form thermally stable TaC with C in the melt pool [32–34]. Table 2 is a summary of the investigations for the inclusion of TaC to improve the high temperature wear resistance of laser cladding Ni-based coatings.

Table 2. Test and key findings of adding TaC to improve wear resistance of coating at high temperature.

Ref.	Substrate	Matrix	Ceramic Phase	Key Findings	Tribological Testing Process, Parameters
Li, 2017 [35]	Ti6Al4V	NiCrBSi	TaC	The addition of TaC obviously refines the microstructure of the coating; the hardness and high temperature wear resistance of the coating are improved	A GHT-1000E high-temperature tribometer; Hard Si_3N_4 ceramic balls (d = 4 mm); Load: 10 N; Temperature: 600 °C; Tliding speed: 0.188 m/s
Yu, 2021 [36]	Medium carbon steel	NiCrBSi	Ta	TaC synthesized in situ has higher hardness and thermal stability, stronger bonding at TaC/substrate intersection	A pin-on-disc tribometer; Al_2O_3 disk; Load: 90 N; Temperature: 25, 300 °C, 600 and 700 °C; Sliding speed: 790 m m/s; Time: 60 min
Yu, 2022 [37]	Inconel 625 Nickel-based alloy	Ni-Al-Cr	Ta, C powder	TaC grains withstand the burden and prevent micro-cutting of debris. Ta inhibits the growth of Al_2O_3 and accelerates the sintering of the oxide layer, forming a dense oxide layer over the wear surface	A pin-on-disc tribometer; Load: 60 N; Temperatures: RT, 300 °C, 550 °C and 700 °C; Time: 1 h; Sliding speed: 0.105 m/s

Lv et al. [35] prepared NiCrBSi/TaC composite coatings on Ti6Al4V surfaces by the mechanical addition method, and 5 wt.% addition of TaC was sufficient to significantly reduce the amount of wear of the coatings at 600 °C. This is due to the dissolution of TaC in the melt pool, which is the initial precipitation as the core of non-uniform nucleation when the melt pool was cooled, accelerating the nucleation efficiency and refining the microstructure. In addition, the solid solution of Ta in the melt pool into TiNi, Ti_2Ni and other intermetallic compounds further enhances the strength of the coating and effectively enhances the high temperature abrasive resistance. Yu et al. [36] mechanically mixed different percentages of Ta powder (0 wt.% to 10 wt.%) with Ni-based powder on the surface of medium carbon steel to study the improvement of the wear resistance of nickel-based coatings by the addition of Ta. As shown in the TEM analysis of Figure 1, Ta combines with C to form a high hardness. Stable bulk TaC phase under the high temperature action of the melt pool, and it is observed under the high-resolution TEM that Ta does not form amorphous phases after reacting with the elements, and the TaC/substrate interface is well bonded. In addition, the oxide layer which develops in the wear surfacing acts as a lubricant during the abrasion process, decreasing the COF during testing and boosting the high temperature wear resistance. Yu et al. [37] prepared NiAlCrTaC composite coatings under the surface of Inconel 625 Ni-based high-temperature alloy and found that the addition of TaC boost the wear resistance of the coatings obviously at 25 °C, 300 °C, 550 °C and 700 °C. At 550 °C, the oxide in the oxide layer of the NiAlCr coating grows dramatically, which results in under-sintering and extensive spalling of the oxide layer, and the COF and Wear weightlessness are noticeably increased. The Ta element in the coating inhibits the growth of Al_2O_3 oxide and promotes the sintering of the oxide layer, thus forming a continuous dense oxide layer on the abrasive surface and reducing the wear loss. At 700 °C, the TaC grains in the NiAlCrTaC composite coating withstand the burden and prevent micro-cutting of debris, thus forming an oxide layer from damage and providing the coating with good wear resistance under high temperature conditions.

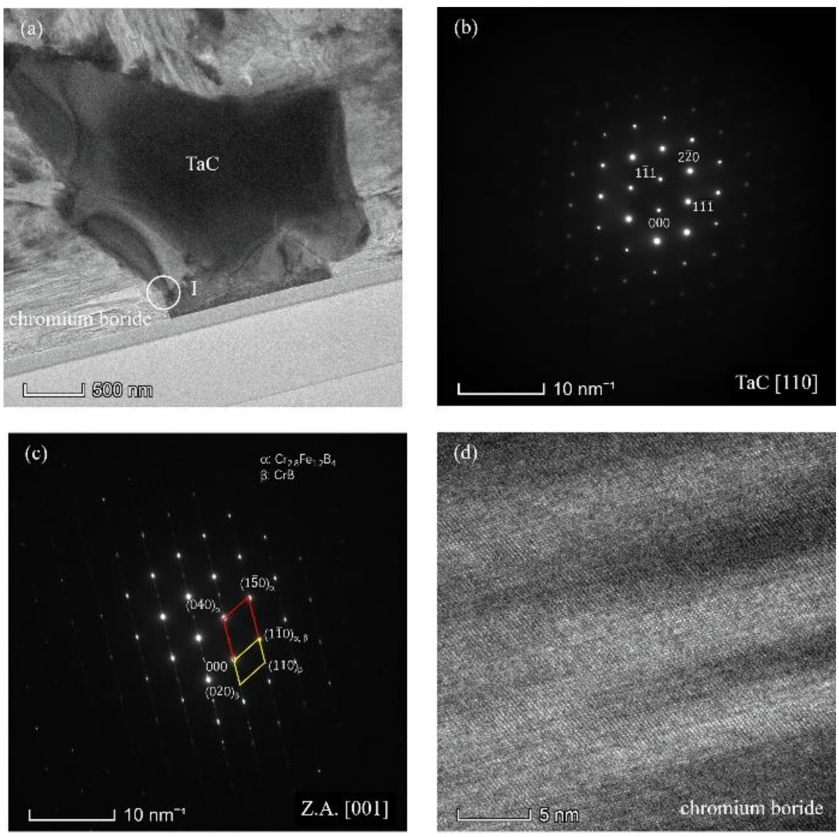


Figure 1. *Cont.*

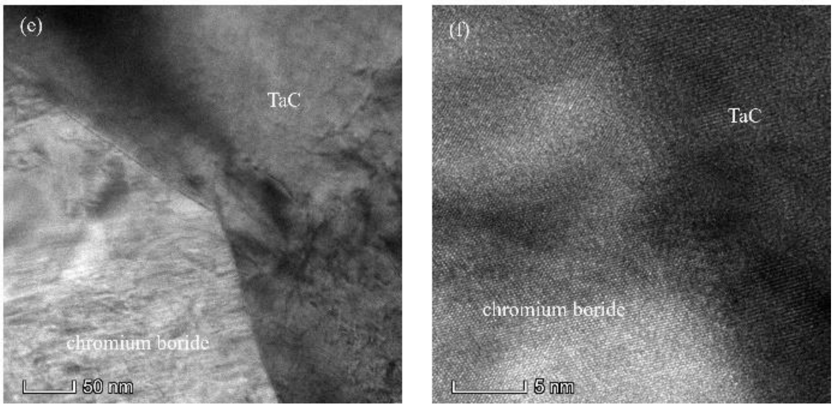


Figure 1. TEM photographs of Ta-containing coatings: (**a**) morphology; (**b**) SAED of TaC; (**c**) SAED of chromium borides; (**d**) HRTEM of chromium boride; (**e**) high magnified view labeled in (**a**); (**f**) HRTEM of the interface between TaC and chromium boride, reprinted with permission from Ref. [36], Copyright 2021 Elsevier.

2.3. Other Ceramic Phase

Table 3 concludes the status of the incorporation of the other ceramic phase to promote the high temperature wear resistance of laser cladding Ni-based coatings.

Zan et al. [38] tried to add a metal-ceramic composite powder NiCr-Cr_3C_2 to Ni45 powder to enhance the high temperature wear resistance of nickel-based coatings, and the abrasive of the coating decreased compared to the matrix. However, the wear loss increased with temperature and the wear resistance was essentially the same as that of the matrix under high temperature conditions. This is due to the stability of Cr_3C_2 decreasing above 600 °C, which makes it difficult to support the wear as a hard ceramic phase. This limits the application of Cr_3C_2 to enhance the high temperature abrasive resistance. ZrB_2 has a melting point as high as 3040 °C and high strength at both room and high temperatures, and as a typical ultra-high temperature ceramic is an ideal additive to promote the high temperature wear resistance of nickel-based coatings [39]. Guo et al. [40] researched ZrB_2 on the high temperature wear resistance of nickel-based coatings and found that the added ZrB2 acts as a hard ceramic phase to support and protect the substrate during the wear process, making only slight abrasion marks on the wear surface.

Table 3. Test and key findings of adding hard ceramic phase to improve wear resistance of coating at high temperature.

Ref.	Substrate	Matrix	Ceramic Phase	Key Findings	Tribological Testing Process, Parameters
Zang, 2015 [38]	20Cr2Ni4A	Ni45	NiCr-Cr_3C_2	NiCr–Cr_3C_2 coating has a better abrasive rate and lower COF	A ball-on-plate friction test; Temperatures: 20, 100 and 300 °C using; SiC ball (d = 10 mm); Load: 3 kg; The stroke: 1000 µm; frequency: 50 Hz Time: 30 min
Guo, 2013 [40]	pure Ti discs	NiCoCrAlY alloy powder	ZrB_2	The addition of ZrB_2 as a hard ceramic phase to support and protect the substrate during the wear process, resulting in only slight wear marks on the surface in the friction test	A SRV-IV friction and wear tester. Si_3N_4 balls (d = 1 cm); Temperature: 20, 100, 300 and 500 °C; Load: 40 N; frequency: 15 Hz; Time: 15 min
Sun, 2022 [41]	Q235 low carbon steel	Ni60AA	Cu, CuMo, CuMoW	The additive of Cu refines the organization of the coating and results in the formation of NiCu solid solution. Resists wear and lubrication	MMQ-02G; The zirconia ball (4 mm); Temperature: RT, 600 °C; Time: 30 min; Load: 30 N; Frequency: 1 Hz

Sun et al. [41] made the first study on the results of Cu, Mo and W to boost the wear resistance of nickel-based coatings by adding W to the powder of Ni60AACuMo composition to prepare the coatings and to investigate their microstructure and wear resistance. The study results demonstrated that WC was generated after the addition of W, and the microhardness of the coating was slightly boosted. While, the preferential precipitation of the WC phase consumed the C element in the γ phase and inhibited the carbide precipitation, the wear resistance decreased.

In summary, the authors concluded that the appropriate addition of hard ceramic phases during coating preparation or in situ ceramic phases in the coating by adding an appropriate amount of elements, is an attractive way of achieving greater high temperature wear resistance of laser cladding nickel-based composite coatings. However, compared with room temperature conditions, the types of hard ceramic phases added to enhance the wear resistance of coatings at high temperature are relatively single, and the current research is mainly focused on WC and TaC. Both TiC and NbC have melting points above 3000 °C and the hardness is also higher, and many studies have indicated that the in situ synthesized NiCrBSi/TiC and NiCrBSi/NbC coatings have good interfacial bonding. Researchers are expected to explore further.

3. Solid Lubricants

Lubricants can be classified as solid, semi-solid and liquid lubricants according to their morphology, but only solid lubricants can meet the wear resistance requirements of materials under high temperature [42]. Researchers have tried to add various solid lubricants to nickel-based alloys for more than a decade since the beginning of the 21st century, and nickel-based self-lubricating alloy systems have been explored [43]. Solid lubricants could be classified into three categories according to the lubrication mechanism: one is lamellar solid lubricants (MoS_2, graphite, Hexagonal boron nitride(h-BN), and others, with the crystal structure shown in Figure 2 [44,45]) due to the weak interplanar cohesive bonds and strong anisotropy between lamellar solid surfaces and the lamellar structure functions as a self-lubricating agent under low shear stress conditions [46]. Another common solid lubricant is soft metal, as shown in Figure 3, which mainly relies on the metal's own low shear strength and strong ductility to form a thin friction layer on the relatively hard contact surface [47]. In addition, as shown in Figure 4, a few chemically stable oxides and fluorides are also employed as high temperature solid lubricants [48]. However, fluorides have not been investigated to enhance the high temperature abrasive resistance.

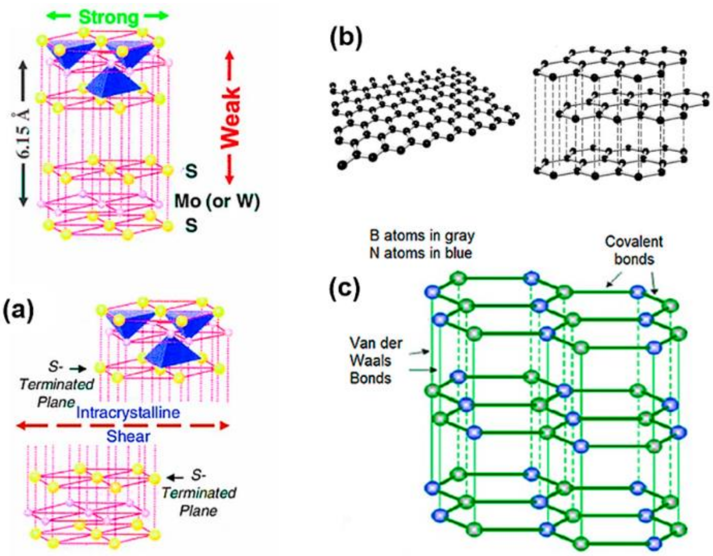


Figure 2. Crystal structure of several typical lamellar solid lubricants: (**a**) MoS_2 (or WS_2); (**b**) A single graphene layer and graphite as a stack of multiple graphene layers; (**c**) h-BN, reprinted with permission from Ref. [44], Copyright 2018 Taylor & Francis and reprinted from Ref. [45].

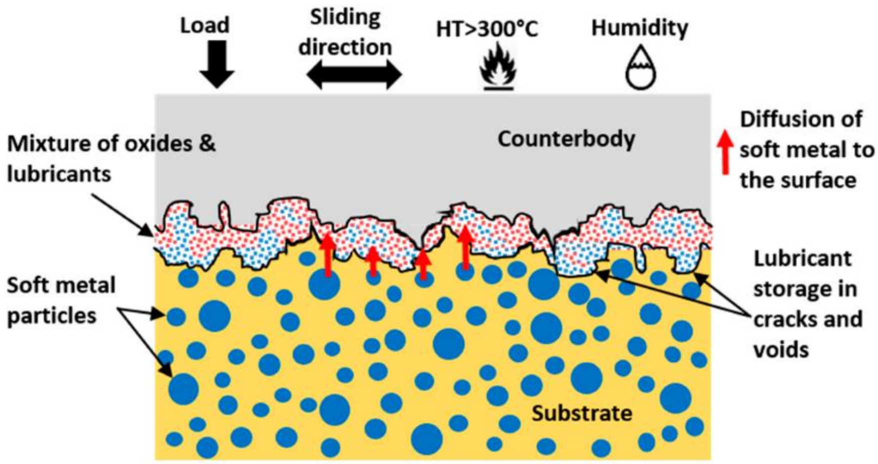


Figure 3. Diffusion mechanism of solid lubrication on soft metal matrix, reprinted from Ref. [45].

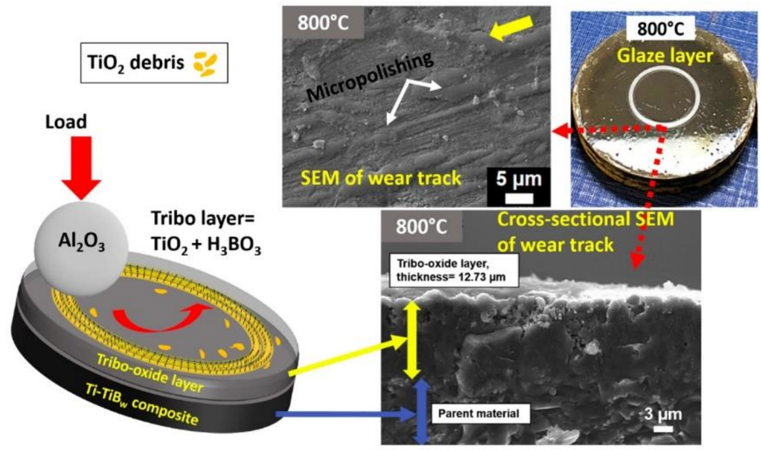


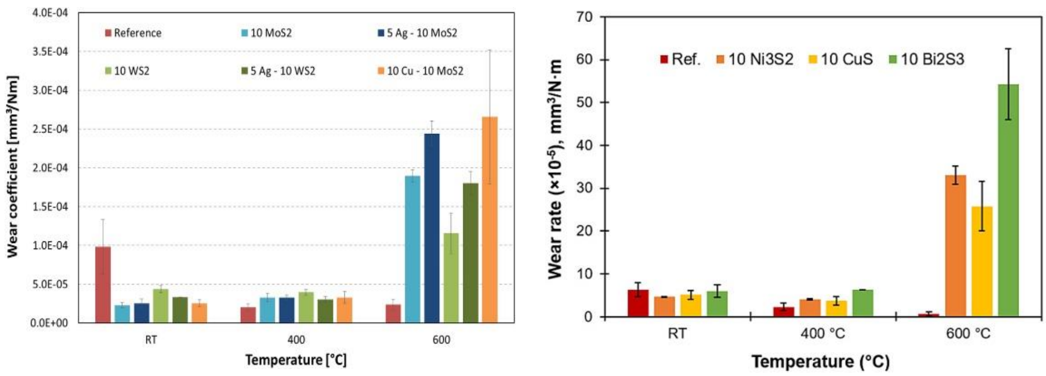
Figure 4. A mechanism to reduce wear at high temperatures by forming a uniform friction layer (composed of TiO_2 and boric acid), reprinted from Ref. [45] and reprinted with permission from Ref. [48], Copyright 2021 Elsevier.

3.1. Lamellar Solids

MoS_2 and graphite have a laminate structure where shearing can easily occur, which can provide self-lubricating properties to the coating, and are common lubricants under normal temperature conditions. However, oxidation occurs above 350 °C for MoS_2 and above 450 °C for graphite. When the temperature increases, such lubricants gradually oxidize to induce degradation of their structure and their lubrication effect is greatly reduced, so few attempts have been made to add MoS_2 and graphite alone to boost the high temperature wear resistance [49].

Although the vast majority of consequences indicate that sulfides have little effect on wear resistance enhancement above 300 °C, researchers have not stopped studying sulfides to boost the wear resistance of nickel-based coatings. The study of adding solid lubricants such as sulfide and Mo to improve the high temperature wear resistance of laser-fused nickel-based coatings is summarized in Table 4.

The team of Prof. H. Torres [50] studied the wear behavior of coatings incorporating MoS_2 and WS_2 at different temperatures. As shown in Figure 5, the addition of Cu and Ag further enhanced the wear resistance at room temperature, however, under high temperature requirements, the friction coefficient increases significantly and the surface wear resistance at high temperature of the coating is somewhat worse than that of NiCrBSi coating. This is primarily attributed to the dissolution and oxidation of sulfides at high temperatures and the formation of more debris on the surface of the coating during the friction test. The effect of three sulfides, Ni_3S_2, CuS, and Bi_2S_3, on the wear resistance of Ni-based coatings was first investigated by the team of Prof. R. Kumar [51] at temperatures of 400 and 600 °C. The coatings with the three components maintained a high hardness at high temperatures. Along with the increase in temperature from 25 °C to 600 °C, the microhardness decreased by about 20%. As shown in Figure 5, the COF of the three coatings with sulfide addition at 400 °C was reduced and more uniform and stable, and the self-lubricating behavior reduced the amount of wear by 40%. However, as the temperature rose to 600 °C, the COF of the three sulfide-added coatings began to fluctuate sharply and the amount of wear increased greatly. This indicates that it is difficult for Ni_3S_2, CuS and Bi_2S_3 to make an effective improvement in the abrasive resistance of Ni-based coatings at 600 °C. Sulfides are unstable and easily oxidized at high temperatures, particularly above 610 °C when the COF of the coating raises sharply, and are not effective in improving the high temperature wear resistance of nickel-based coatings [52]. The authors concluded that the encapsulation on the surface of sulfide by chemical plating proposed by Liu [53] can effectively inhibit its decomposition but also can boost the compatibility with the substrate.



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

Figure 5. The results of sulfide on the friction coefficient and wear rate of coating: (**a**) Wear coefficient, reprinted with permission from Ref. [50], Copyright 2018 Elsevier; (**b**) Wear rate, reprinted with permission from Ref. [51], Copyright 2023 Elsevier.

Dilawary et al. [54] incorporated an Mo element to Ni-based coatings and the oxide layer was formed by oxidation of debris at the coating surface during wear at 700 °C. MoO_2, an oxide of Mo, increased the hardness while acting as a solid lubricant to reduce the wear coefficient of the coating. Sun et al. [41] prepared Ni60AACuMo composite coatings by adding Mo again on top of the added Cu powder, but the frictional wear results at 600 °C showed that the wear resistance of the coatings decreased. This is principally a result of the serious decrease in hardness of the Ni60AACuMo coating after the addition of Mo, which led to the hard ceramic phase flaking off from the substrate under the load during the frictional wear process, and the formation of abrasive particles aggravated the wear of the coating during the subsequent frictional wear test.

Ti_3SiC_2 has a hexagonal lamellar structure and is a potential solid lubricant with self-lubricating properties [55]. Liu et al. [56] added 5, 10, and 15 wt.% of Ti_3SiC_2 to Ni45 powder to promote the high temperature wear resistance of the coating. The wear of the coating was significantly reduced by the synergistic effect of the coating oxide film and Ti_3SiC_2, but the experimental analysis revealed that different additions had different strengthening mechanisms on the microhardness of the coating. When a small amount of Ti_3SiC_2 was added, it mainly acted as a heterogeneous nucleation core to promote grain refinement, while when the added amount was higher, Ti_3SiC_2 enhanced the hardness of the coating by causing lattice distortion and diffusion strengthening.

Table 4. Tests and crucial findings on the addition of solid lubricants to enhance the high temperature wear resistance of coatings.

Ref.	Substrate	Matrix	Ceramic Phase	Key Findings	Tribological Testing Process, Parameters
Torres, 2018 [50]	stainless steel	NiCrBSi	MoS_2, WS_2, Ag, Cu	The high temperature wear resistance of the coating decreases after the addition of Cu and Ag	AISI 52,100 bearing balls with a diameter of 10 mm; Load: 50 N. Temperature: RT, 150, 300, 400, 600 °C; Wear time: 900 s; Stroke length: 2 mm
Kumar, 2023 [51]	stainless steel	NiCrBSi	Ni_3S_2, CuS, Bi_2S_3	The coating retains high hardness at high temperatures, but the friction coefficients all become unstable	Ball-on-plate configuration; Load: 50 N; Frequency and stroke: 25 Hz and 0.2 cm; Sliding speeds of 10 cm/s. Time: 900 s; Temperature: 25, 400, 600 °C
Dilawary, 2018 [54]	AISI 4140 steel	NiCrBSi	Mo	MoO_2 can not only enhance the hardness but also act as a solid lubricant to decrease the wear coefficient of the coating	A ball-on-disc configuration; Load: 3 N; Contact pressure: 1.0 GPa; Temperatures: RT, 300, 500 and 700 °C
Sun, 2022 [41]	Q235	Ni60AA	Cu, CuMo, CuMoW	Mainly due to the fine and uniform microstructure and the formation of NiCu solid solution phase, the coating with the addition of Cu exhibits excellent wear resistance	MMQ-02G; The zirconia ball with a radius of 4 mm; Temperature: RT, 600 °C; Time: 30 min; Load: 30 N; Frequency: 1 Hz
Liu, 2021 [56]	304 stainless steel	Ni60	Ti_3SiC_2	Ti_3SiC_2 synergizes with Ni60 oxide film for better lubrication performance at high temperatures	Si_3N_4 ball (diameter: 5 mm); Load: 5 N; Time: 30 min; The rotation velocity is 560 r/min. Temperature: 25, 600 °C

H-BN is an isomer of boron nitride, known as "white graphite" due to its hexagonal dot matrix crystal structure similar to graphite and its good lubricity [57]. Its crystal structure determines that its shear properties are anisotropic, preferentially shearing in the direction parallel to the base or perpendicular to the c-axis when subjected to shear forces [58,59]. In addition, h-BN has strong oxidation resistance and high thermal stability, so it is widely applied to promote high temperature wear resistance of nickel-based coatings. Studies on h-BN to ameliorate the high temperature wear resistance of coatings are summarized in Table 5.

Zhang et al. [60] prepared Ni60 + h-BN coatings on Ti-6Al-4V surface, and XPS, SEM, and EDS analyses demonstrated that most of h-BN decomposed under the action of laser and undergone in situ reaction in the melt pool to synthesize TiB, TiN and TiO phases to boost the hardness and wear resistance of the coatings. The TiN phase boosts the hardness and wear resistance of the coating, and the NiO, TiO_2, Al_2O_3 and other metal oxides in the coating act as lubrication and wear reduction under the high temperature environment, and the synergistic effect makes the coating obtain good wear resistance even under the high temperature condition. Lu et al. [61] produced Ni60 + h-BN coating over Ti-6Al-4V surface, and the dry sliding wear test conditions resulted in the best wear resistance of the Ni-10 wt.% h-BN composition at 25, 300, and 600 °C. The wear morphology of the coating surface for each group at 600 °C is shown in Figure 6. The wear mechanisms are minimal abrasive wear and brittle fracture as well as the breakdown of the transfer layer. This is primarily caused by the fact that most of h-BN decomposes to produce TiB_2 to promote the hardness of the coating, and the residual h-BN forms a lubricating film on the friction surface to ensure the abrasive resistance of the coating under high temperature conditions. Zhang et al. [62] produced Ni/h-BN coating on the surface of 1Cr18Ni9Ti, and the high temperature wear resistance of the coating was promoted compared to other groupings at the same temperature. The wear resistance of the coating increased instead with the increase of temperature in the range of 0–600 °C, and its wear resistance decreased in the range of 600–800 °C due to the decrease of hardness of the coating. Liu et al. [63] produced nickel-based coatings by adding WS_2 + h-BN with self-lubricating properties and hard ceramic phase TiN to Ni60, and the experimental results indicated that the average microhardness of the coating was 1.3 to 1.7 times higher than that of the substrate, the COF of the coating was stable around 0.3458, and the wear resistance of the coating was significantly improved.

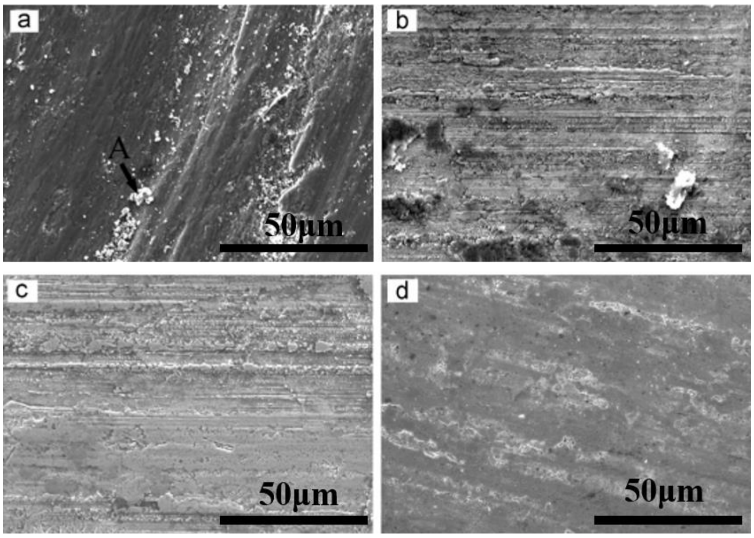


Figure 6. SEM micrographs of the surface wear morphology of the coatings at 600 °C: (**a**) substrate; (**b**) Ni60 coating; (**c**) Ni60 coating with 5% h-BN addition; (**d**) Ni60 coating with 10% h-BN addition reprinted with permission from Ref. [61], Copyright 2016 Elsevier.

C-BN has an outstanding hardness, thermal stability and wear resistance; h-BN has exceptional thermal stability, chemical inertness and lubricity; and c-BN can be transformed into h-BN at 1540 °C [64–66]. Zhao et al. [67] investigated the effect of h-BN (A1) and c-BN (A2) on the properties of two boron nitride isomers in the range of 25–800 °C, based on the effect of Ni60 + MoO_3 composite coatings on the structure and properties. Wrapping a copper layer around the interface of c-BN particles can both decrease the laser absorption of c-BN and prevent the conversion of all c-BN particles to h-BN, and react with MoO_3 to form $CuMoO_4$ solid lubricant. XRD analysis showed that under the high temperature of the laser cladding melt pool, some of the c-BN changed to h-BN, while the other part reacted with the elements in Ni60 powder to form Cr(Mo)B, Cr_5B_3, CrN and MoN enhancers. The test outcomes indicate that the composite coatings containing c-BN have higher hardness and wear resistance from 25 °C to 800 °C with different degrees of improvement, and the wear rate is reduced by 77%, 61%, 29%, 46% and 39%, respectively. This is due to the increased hardness of the composite coating by the retained c-BN. A study by Yang et al. [68] showed that the mismatch rate of the lattice constant between the matrix and the reinforced phase is an important factor affecting the strength of the interfacial bond. The lower the mismatch rate, the stronger the interfacial bond. The mismatch rate of Cr(Mo)B and γ-(Ni, M) matrices was computed by the following equation [69]. Combined with the TEM image in Figure 7, the interatomic distance was measured. The calculated results show that $\delta_{A1} = 63.0\%$ and $\delta_{A2} = 5.15\%$, indicating that the interfacial bonding strength between the reinforcing phase and the substrate in the A2 coating was higher. The hardness and interfacial bonding strength of the coating with the addition of c-BN were increased, in addition, the high temperature wear resistance of the coating was significantly enhanced compared to that for h-BN.

$$\delta = \frac{|a\alpha - a\beta|}{\frac{a\alpha + a\beta}{2}} \quad (1)$$

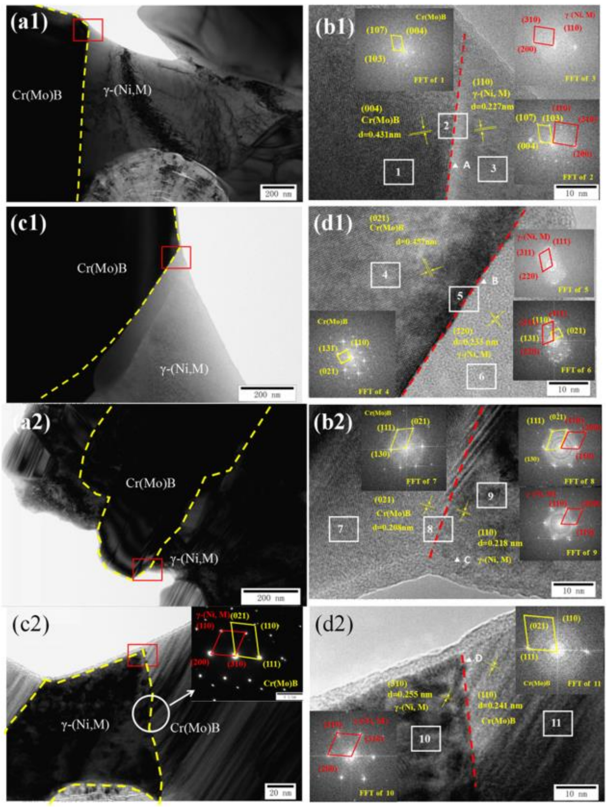


Figure 7. Results of TEM analysis. (**a1**,**c1**): bright field phase of A1; (**a2**,**c2**): bright field image of A2; (**b1**,**d1**): HRTEM and FFT results of selected region of A1; (**b2**,**d2**): HRTEM and FFT results of selected region of A2, reprinted with permission from Ref. [67], Copyright 2021 Elsevier.

Table 5. Test and key discovery of adding solid lubricant to improve wear resistance of coating at high temperature.

Ref.	Substrate	Matrix	Ceramic Phase	Key Findings	Tribological Testing Process, Parameters
Zhang, 2019 [60]	Ti6Al4V	Ni60	h-BN	The h-BN particles were decomposed to synthesize TiB and TiN in situ in the melt pool to resist wear. The metal oxides produced at high temperatures act as a lubricant	A ball-on-disk type friction and wear test machine; Si_3N_4 ceramic balls of Φ 6 mm; Rate: 5 Hz; Load: 5 N; Duration: 60 min
Lu, 2016 [61]	Ti6Al4V	NiCrBSi	h-BN	Most of the h-BN decompose to produce TiB_2, which boosts the hardness of the coating. The residual h-BN acts as a lubricant during friction	A ball-on-disk tribo-meter; Temperature: 20, 300, 600 °C; The counter-body was a Si_3N_4 ceramic ball (d = 4 mm); Duration: 30 min
Zhang, 2008 [62]	1Cr18Ni9Ti	Nickel powder	h-BN	At lower temperatures, coating wear resistance increases with increasing temperature; in the range of 600–800 °C, coating wear resistance decreases due to the decrease in hardness.	A GWY-2000 ball-on-disc friction and wear tester; Si_3N_4 ceramic (d = 10); Load: 100 N; Sliding speed: 0.226 m/s; Duration: 20 min

Table 5. *Cont.*

Ref.	Substrate	Matrix	Ceramic Phase	Key Findings	Tribological Testing Process, Parameters
Liu, 2020 [63]	TC4	Ni60	TiN, WS_2 + h-BN	The addition of WS_2 + h-BN and TiN increased the average microhardness of the coating by 1.3–1.7 times, and the friction coefficient of the coating was stable	A pin-and-disc friction and wear tester. Duration: 30 min; Load: 50 N, the speed was 100 rpm, the grinding radius: 3 mm. WC ball (d = 9.5 mm)
Zhao, 2021 [67]	Q235	Ni60	Cu/h-BN + MoO_3	The breakdown of c-BN boosts the bond strength between Cr(Mo)B and the substrate. At the same time, h-BN provides a low coefficient of friction over a broad range of temperatures	A dry sliding pin-on-disk device. Al_2O_3 balls (d = 5 mm); load: 3 kg; rotating speed: 50 rpm; The rotation diameter 0.1 cm; friction duration: and 0.5 h
Liu, 2022 [70]	45# steel	Ni60	Cu	Cu plays the friction transfer film and oxidation double-layer self-lubrication. Ni60-5 wt.%Cu composition of the coating, the coefficient of friction at 600 °C is 0.267	High temperature tribometer with Si_3N_4 ceramic balls on disk using Φ 6 mm; load: 5 N; time: 30 min; temperature: RT, 600 °C.

3.2. Soft Metals

Cu has a face-centered cubic crystal structure with an atomic radius similar to that of Ni and can combine with Ni atoms to form (Ni, Cu) solid solutions under high temperature conditions [71]; Mo oxides can enhance the microstructure and properties of the coatings [72]. Liu et al. [70] added different levels of Cu to Ni60 powder to study the effect of Cu amount on the tissue evolvement and tribological behavior in laser-fused Ni60 composite coatings. Since Cu acts as a friction transmission membrane and an oxide double layer self-lubrication, the coatings with Cu exhibit good wear resistance, especially the coatings with Ni60-5 wt.%Cu composition, the friction coefficient at 600 °C is only 0.267. Coatings were prepared by adding Cu, CuMo and CuMoW to Ni60AA and their wear resistance was evaluated at 25 and 600 °C, respectively. The Ni60AACu coatings were found to have the best wear resistance [41]. This is mainly due to the fact that the microstructure of the coating becomes uniform and fine after the addition of Cu, and Cu replaces part of Ni to form NiCu solid solution, which acts as a lubricant in the frictional wear process and reduces the wear of the coating [70]. The hardness of the Ni60AACuMo coating decreases severely after the addition of Mo, resulting in the hard ceramic phase flaking off from the substrate under the action of external forces during the friction process. The formation of abrasive particles aggravates the wear of the coating during the subsequent friction wear test. Since soft metals soften at higher temperatures and their wear resistance decreases significantly in service environments above 500 °C, more existing studies have prepared coatings by adding soft metals together with other hard ceramic phases or lubricants [73,74]. The synergistic action of two or more lubricants can stabilize the high temperature wear resistance of the coatings at a high level, such as constituting Ag/MoS_2/G [75], Ag/WS_2/h-BN [76], Cu/c-BN/MoO_3 [71], Cu/MoS_2 [50], Cu/WS_2 [77], Mo_2N/MoS_2/Ag [78], and Ag/MoS_2 [79] alloy systems.

4. Conclusions

In the aerospace, automotive and petrochemical industries, some parts are used in high temperature environments for long periods. Improvement of the high temperature wear resistance of the material is essential to extend the service life of the equipment and diminish equipment wear. This paper reviews the current status of research on improving the high temperature wear resistance of laser-cladding nickel-based coatings and draws the following conclusions:

(1) The wear resistance of the coating is highly correlated with the hardness. The addition of a hard ceramic phase can make the coating maintain a relatively high hardness under the high temperature condition and thus boost the high temperature wear

resistance of the coating. Compared with a wide variety of added phases at room temperature, the hard ceramic phase added to enhance high temperature wear resistance is relatively single. The improvement effect of a large number of hard ceramic phases on high temperature wear resistance is yet to be explored. Future work could revolve around a wider range of hard ceramic phases to improve the high temperature wear resistance of coatings. At the same time, the synergistic effect of various hard phases can be studied. In addition, the effects of an electric field, magnetic field, vibration and other auxiliary treatments on high temperature wear resistance of nickel-based coatings can be systematically studied.

(2) The interplanar cohesive bonds between the lamellar solid surfaces are weak, and the lamellar structure plays a self-lubricating role under low shear stress conditions. Soft metal's own low shear strength and strong ductility in the relatively hard contact surface form a thin layer of soft friction layer. These two types of solid lubricants in high temperature conditions can play a useful role in improving the wear resistance of nickel-based coatings.

(3) The existing lubricant takes effect in a narrow range, and the wear resistance of the coating decreases remarkably after exceeding the applicable temperature range. Future solutions: one is to develop new high temperature lubricating materials with better lubrication effect and wider temperature ranges. The other is through the synergistic effect of multiple lubricants, the high temperature wear resistance of the coating can be maintained at a high level.

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