Preparation of high wear resistance nickel based WC coating by carefully adjusting interface structure

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Abstract

In recent years, many scholars have paid attention to wear-resistant coatings for shield machine cutterheads due to their very high consumption rates. Among these coatings, nickel-based tungsten carbide (Ni-based WC) is one of the best, showing both corrosion resistance and wear resistance. However, to further improve the wear resistance of such coatings, there are still numerous issues that need to be resolved. Herein, a new method, distinct from conventional methods, is presented. Specifically, the brittle phase W2C is not widely regarded as the main wear-resistant phase, but we were surprised to find that careful adjustment of its rigid structure can yield satisfactory results. Experimental results and first-principles simulations have indicated that the friction coefficient and weight loss of a coating with a suitable distribution of W2C are only half of those of a traditional Ni-based WC coating (about five times higher than those of the substrate), which can mainly be attributed to the excellent thermal expansion coefficient and hardness of the W2C phase. As we expected, the surface morphology of the material after wear revealed that the suitable W2C layer has a well-defined friction morphology. We hope to provide new ideas for the study of Ni-based WC coatings in shield machine cutterheads.

1. Introduction

In recent years with the rapid development of urban rail transit, people have put forward an urgent demand for wear-resistant coating of shield machine cutterhead [1–3]. Among these coatings, nickel-based tungsten carbide coating (Ni-based WC) has attracted much interest for its excellent wear resistance, service life, and other properties [4]. However, the performance of Ni-based WC coating can not fully meet the current actual demand, due to the interface between WC particles and Ni-base alloy being prone to stress concentration, which would lead to coating crack extension, peeling, and a series of problems [5, 6]. Therefore, it is crucial to develop a high wear resistance and high stability of Ni-based WC coating.

In order to solve those dilemmas, some researchers have done some work on preparation processes. For instance, by laser hot-wire deposition, high volume fraction of the reinforcements with ex situ eutectoid-structured WC/W2C particles can be obtained, thus the coating hardness and wear resistance are improved to about 3.5 times and 4.5 times more than that of substrate [7]. Instead, using cold spraying technology to prepare Ni-WC composite coating, can effectively avoid the WC decarbonization phase (W2C phase), which contributes to the formation of WC coating with higher filling rate [8]. According to the above explanations, the true modification mechanism of Ni-based WC coating is not fully understood.

Recent mechanistic studies of wear resistance of intermediate transition phase W2C have shown that W2C seems to be a potential for interface adjustment. Classically, Tillmann W et al carried out high-speed arc spraying
of WC-W2C iron-based coatings results in WC-W2C particle-enhanced coating properties through a dense microstructure, good bond strength to the substrate, and the smooth surface of WC-W2C iron-based coatings results in WC-W2C particle-enhanced coating properties through a dense microstructure, good bond strength to the substrate, and the smooth surface of WC-W2C particles resulting in the growth of nano-sized W2C particles in situ, thus reinforcing the composite interface. Hence, the ultimate wear resistance of wear-resistant coatings is enhanced by the introduction of W2C particles resulting in the improvement of coating properties, which has also been confirmed in coating applications. However, although these endeavors, these studies are limited to the interrelationship between interfacial tuning and wear resistance, while theoretical predictions and computational simulations are still not clearly available for mechanical understanding [14–16].

Therefore, Therefore, this paper discusses the thermodynamic mechanism of the reaction between tungsten and carbon in tungsten carbide and calculates the microstructure of the primary phase interface by advanced first principles. It was demonstrated that the main phase with soft secondary phase reinforcement was obtained through thermomechanical control, thereby upgrading the wear resistance and stability of the nickel-based tungsten carbide coating and addressing the problem of spalling and cracking of the shield blade coating to extend its service life and reduce costs. More importantly, the slow release mechanism of intermediate transition relative coating interface was found out which can put forward new theoretical guidance for the research of wear-resistant materials.

2. Experimental

2.1. Materials

In the present study, 304 L stainless steel (100 mm × 100 mm × 5 mm, Alibaba, Shanghai) was used as the substrate, and its chemical composition is shown in table 1. The coating material is a Ni-WC powder (40 wt% Ni, 60 wt% WC, Alibaba, Shanghai) with a particle size of 100–150 mesh.

2.2. Plasma surfacing process

The substrate (304 L stainless steel) was first subjected to high-energy shot peening derusting, ultrasonic cleaning with anhydrous ethanol, and air-drying treatment [17]. Before coating, the substrate was annealed at 350 °C for 2 h to eliminate any residual stress therein [17]. Plasma coating was carried out using DML-V03BD and BM09DF three-way machine tools, the operational parameters of which are listed in table 2. Considering the melting points of WC and Ni powder, repeated experimental welding gave coatings with a good metallurgical bond above welding currents of 140 A; thus, three welding currents of 140 A, 160 A, and 180 A were selected for experiments under otherwise identical conditions. After coating, the coated material was cut into equal 10 mm × 10 mm squares using a wire-cutting machine, which were easy to observe utilizing a scanning electron microscope (SEM). Abrasive papers of 400 #, 600 #, 800 #, 1000 #, 1500 #, and 2000 # were then sequentially applied for preliminary grinding and fine grinding [13].

2.3. Characterization

Surface microstructures of coating layers were observed with a Hitachi 4800 SEM, which was equipped with energy-dispersive spectroscopy (EDS) attachment to analyze the elemental compositions and distributions. A Tecnai G2 20S-TWIN transmission electron microscope (TEM), operated at a working voltage of 160 kV, was used to observe the microstructures of the samples. A D/ max-2200 x-ray diffractometer (XRD) was used to determine the phase composition of the coating layer, employing a Cu-Kα x-ray source (1486.6 eV, λ = 0.15406 nm), a working potential of 30 kV, a current of 30 mA, a step size of 0.5°, and a scanning speed of 4°·min⁻¹ over the range 10°–90° [14, 15]. To further investigate elemental valence states on the surface of the coating layer, x-ray photoelectron spectroscopy (XPS) on a PH15000 instrument was used (Al x-ray source). The effect of interfacial reaction on friction resistance was investigated using HSC Chemistry software. The friction and wear properties of the coating were tested with an MFW-02 reciprocating friction and wear testing machine, employing a load of 60 N, a test time of 20 min, and a running speed of 200 rad min⁻¹. Three-dimensional surface profiles of the coating layer were obtained using an atomic force microscope (AFM, Nanoscope V, MultiMode®8, Bruker).

Table 1. Chemical composition of 304 stainless steel.

| Element | C  | Si  | Mn  | P   | S   | Ni  | Cr  | Fe   |
|---------|----|-----|-----|-----|-----|-----|-----|------|
| Mass fraction/% | <0.08 | <1.00 | <2.00 | <0.045 | <0.03 | 8.0–10.5 | 18–20 | Bal   |
Table 2. Parameters in plasma surfacing.

| Rated power/(KVA) | Welding speed/(mm min^{-1}) | Powder feeding speed/(rad min^{-1}) | Welding torch height/(mm) | Flow rate of arcing gas/(L/h) | Protective gas flow/(L/h) | Flow rate of powder feeding air/(L/h) |
|-------------------|-----------------------------|------------------------------------|---------------------------|------------------------------|--------------------------|--------------------------------------|
| 17.8              | 200                         | 30                                 | 10                        | 60                           | 600                      | 60                                   |
2.4. First-principle calculation

All calculations were performed using the first-principles total energy program CASTEP [16]. Here, the plane wave pseudopotential describes the electron wave function, and the generalized gradient approximation (GGA-PBE) is used to deal with the exchange-correlation function. The cut-off energy is 400 eV. The convergence precision of energy is $10^{-4}$ eV cell, and the convergence precision of force is $0.02$ eV Å$^{-1}$, so as to build the interface structure for calculation. A vacuum model with periodicity should be built when building the crystal plane model. Brillouin zone sampling was carried out using Monkhorst–Pack k-point meshes [17]. The structures were optimized by the conjugate-gradient algorithm method. To further verify the mechanical stability of these polymorphs, the elastic constants are calculated with the strain-stress method [18]. Besides, the bulk modulus $B$ and the shear modulus $G$ are estimated via the Voigt-Reuss-Hill approximation by using the obtained elastic constants $C_{ij}$. Young modulus and Poisson ratio are calculated in accordance with the formulas $Y$ and $v$ [19]. The theoretical Vicker’s hardness is estimated by the model. The details of convergence tests have been described elsewhere [20].

3. Results and discussion

3.1. Thermodynamic analysis of interfacial reactions

As shown in figure 1, WC and W$_2$C belong to the cubic and orthogonal crystal system respectively with space group of Pm3m and Pnmm [21]. In this work, Ni-based WC interface structure and crystal structure are established and can be observed in figures 1(a) and (b). The coefficients of thermal expansion of Ni, WC, and W$_2$C crystals calculated by first principles are given in figure 1(c) [22]. When the temperature exceeds 200 K, the average thermal expansion coefficient of the W$_2$C phase, Ni and WC particles are $22.312 \times 10^{-6} \text{K}^{-1}$, $50.343 \times 10^{-6} \text{K}^{-1}$ and $13.245 \times 10^{-6} \text{K}^{-1}$, respectively. Due to the large thermal expansion difference between WC and Ni particles, the coating is easy to peel off, W2C has better high-temperature heat resistance and is suitable as an interfacial transition phase, where stress-relieving effects exist to increase the bonding between Ni and WC particles. The coefficient of linear expansion of W$_2$C is relatively flat and the value is not large. For WC/Ni composites, the generation of interfacial phase W$_2$C helps to regulate the difference of thermophysical properties between Ni and reinforcing particles WC, thus effectively mitigating the stress concentration at the junction of Ni and reinforcing particles, which leads to particle detachment [23, 24].

![Figure 1](image_url)

**Figure 1.** Thermodynamic analysis of the interface structure of Ni-based WC coating. (a) Interface structure of the coating, (b) crystal structures of the WC and W$_2$C phases, (c) plots of thermal expansion coefficients of Ni, WC, and W$_2$C crystals derived from first-principles calculations, (d) plots of Gibbs free energies for reactions according to equations (1)–(4) at different temperatures.
It is apparent that W2C is dispersed in the matrix as an intermediate phase. In general, to clearly understand the mechanism of the formation of the second phase \[ \text{(12)} \], at the high temperature of a plasma arc, the main possible metallurgical reactions in the W-C system to be considered are as follows \[ \text{(13)} \] :

\[
\begin{align*}
2WC & = W_2C + C \\
WC & = W + C \\
W_2C & = 2W + C \\
W2C & = WC + W
\end{align*}
\]

HSC chemistry analysis software was used to calculate the Gibbs free energies associated with reactions according to equations \( \text{(1)} \)–\( \text{(4)} \) at different temperatures, and the results are shown in figure 1(d). Apparently, in the plasma arc coating process of W-C systems, the reactions according to equations \( \text{(1)} \) and \( \text{(4)} \) are negative in a certain temperature range. Consequently, the formation and decomposition of W2C is thermodynamically possible. We know that the ease with which a chemical reaction can occur depends mainly on the reaction Gibbs energy \( \Delta G \) the degree of negative. Therefore, it can be seen from the thermodynamic analysis that equations \( \text{(2)} \) and \( \text{(3)} \) would not proceed in the molten liquid pool \[ \text{(26)} \]. As can be seen from figure 1(d), when the temperature exceeds 2615 K, the free energy associated with \( 2WC = W_2C + C \) is lower, so WC particles in the coating will preferentially melt and decompose into the hard W2C phase and free C at high temperatures. It can also be seen that when the temperature is lower than 1690 K, the stability of W2C in the coating decreases, and W2C begins to transform into WC and W phases. This means that at high temperature, the tungsten carbide particles melt at high temperature and undergo metallurgical reaction, and decompose into W2C and C \[ \text{(27)} \]. In summary, WC particles melt at high temperature and undergo metallurgical reaction to decompose into W2C and C.

Using the Voigt–Reuss–Hill approximation, the three–dimensional distribution of WC and W2C elasticity performance was evaluated by ElasticPOST code \[ \text{(28)} \]. Figure 2 shows the mechanical properties derived from the elastic constants in different directions, the 3D modulus surfaces of WC and W2C deviate from the sphere, indicating that the Young’s modulus is anisotropic, further predicting the microcracking \[ \text{(29)} \]. Figures 2(a) and (c) shows that the Young’s modulus of WC and W2C are 570.56 GPa and 430.71 GPa, respectively, and the theoretical predicted hardness values of 34.82 GPa and 16.77 GPa in figures 2(b) and (d). It is noteworthy that the \([001]\) crystal hardness of WC is significantly higher than that of W2C, while the opposite is true for W2C.
which is more favorable for interfacial bonding and stable interfacial phase formation due to the cluster dragging effect and the ability of W₂C to maintain good wettability with WC.

3.2. Microstructure and phase analysis

In previous work by Weng et al it has been shown that the coatings prepared by Ni-60% WC are dense structures and that they are continuous and uniformly distributed [30]. Hence, the WC particle distribution was controlled by adjusting the welding process parameters. The SEM morphology of the surfacing coatings with different welding currents is shown in figure 3, which presents the grayish-white central area of WC particles, the silver-white area of WC melting and diffusion, and the outermost dark gray area of Ni-based molten pool. [14] In addition, it can be observed that the W₂C particles of the coating appear needle-like or dendritic crystals have edges and corners that are present in the nickel-based molten pool as secondary phases. There are different degrees of melting and diffusion phenomena, and the diffusion direction is from the white central area to the surrounding silver-gray area. The sizes of the melting and diffusion areas increase with the increasing welding current. Around the WC particles, there is a small amount of an acicular phase [31], the needle length and content of which depend on the welding current [32]. More significantly, the needle-like phase as stable is a symbol of favorable chemical and metallurgical bonding between the substrate and the coating [33]. The unmelted WC particles inhibit grain growth, thereby achieving grain refinement to form the needle-like phase, and the hard phase of the interlaced needle-like organization is distributed in the coating, which can greatly enhance the hardness and wear resistance of the coating [34–36].

As illustrated in figure 3(a), when the welding current is 140 A, it can be seen some WC particles melted and decomposed into whisker-like dendrites at high temperature. The inner layer structure of this area is uniform and dense, while the outer layer is a large number of Ni-based molten pool areas, which scattered with a small number of broken carbide particles and a large number of pores and cracks. When the current is increased to 160 A, the microstructure of the coating in figure 3(b) changes greatly. Not only does the density and homogenization of the Ni-based pool area increase to a great extent, but the length and number of the needle-like microstructure also increase to a great extent. And it is distributed around the WC particles in a cross-superimposed way, forming a good dispersion and strengthening phase. When the current goes up to 180 A, it can be observed that the length and number of acicular structures are greatly reduced, and short fibrous
dendrites are densely distributed around the acicular structures. A large number of pores exist in the central region of WC, and at the same time, it can be found that part of the dendritic structures have separated from WC particles and are distributed in the nickel-based molten pool, as shown in figure 3(c). Figure 3(d) illustrates the surface of the surfacing coating was analyzed by x-ray diffractometer. As can be seen, the surfacing layer is mainly composed of Fe$_{0.64}$Ni$_{0.36}$ phase, WC, W$_2$C, and free state C. With increasing welding current, the content of WC in the surface layer varied accordingly, suggesting an effect on the relative stabilities of WC and W$_2$C. The results may be interpreted in terms of WC particles melting and decomposing to form W$_2$C at high temperature, forming a thick molten and diffusion zone around them, which may suggest the formation of a new phase and dissolution of W in the Ni matrix, in line with the results of Myalska et al. [37].

At a welding current of 140 A, the negative temperature gradient is larger and the cooling rate of the molten pool is faster. Only a small amount of W$_2$C is transformed into WC in the cooling process. In addition, the interface binding force between the matrix and WC particles will decrease with increasing WC particle content [38, 39]. At a welding current of 160 A, more WC decomposes into W$_2$C at high temperature. As the negative temperature gradient is smaller and the cooling rate is slower, more W$_2$C is transformed into WC upon cooling, and the WC transition layer is the result of the selective dissolution of W$_2$C. At a high welding current of 180 A, more WC particles decompose to W$_2$C. Upon cooling, only part of the W$_2$C phase reverted to WC, so overall W$_2$C remained dominant, consistent with the findings in a previous study [40].

To further determine more clearly the diffusion and microstructure of WC particles and Ni-based melt pool elements in the overlay coating, figure 4(a) shows an EDS line scan after the WC particles. The coating is mainly composed of W, Fe, Ni, and C elements, with the W$_2$C phase generated 10–40 nm away from the Ni particles. Figure 4(b) shows the different degrees of dissolution diffusion in the crystalline surfaces of WC crystals (1 0 0) in clusters. Combined with figures 1, 3, and 4 the existence of W2C particles can be successfully speculated. Since the melting point of WC is 2870 °C and the melting point of Ni is 1453 °C, during the overlaying process, the alloy powder melts on the surface of the tungsten carbide particles when it enters the molten pool, and the interior is not melted. Accordingly, as the temperature drops with the solidification process, respectively, around the carbide after diffusion, a thicker layer of melt diffusion zone is produced around the tungsten carbide particles [41]. It was also noted that tungsten and carbon in the acicular carbide diffused into the melt pool, and nickel and iron in the melt pool diffused into the acicular carbide. The amount of tungsten and carbon in the base metal decreases gradually with increasing distance from the carbide, with localized high carbon peaks, while the amount of nickel and iron decreases with decreasing distance from the needle carbide [42].

![Figure 4](image_url)
Figure 5(a) shows the full-scan XPS pattern of a coating obtained at a welding current of 160 A, and the corresponding high-resolution C 1s and W 4f patterns are shown in figures 5(b) and (c), respectively. The XPS pattern was corrected by Gaussian fitting of the C1s energy spectrum. Figure 5(a) confirms that the main surface elements were Ni, W, and C. The W4f pattern in figure 5(c) consists of two pairs of overlapping peaks, from which binding energies of \( \text{BE}_{W_4f_5/2} = 33.997 \text{ eV} \) and \( \text{BE}_{W_4f_7/2} = 32.597 \text{ eV} \) can be derived. These peaks show incomplete symmetrical fittings, thus demonstrating the presence of the W4+ valence state in the coating. When the welding current was 160 A, the carbide on the surface of the coating was mainly WC, consistent with the results of thermodynamic analysis.

### 3.3. Coating friction analysis

Figure 6(a) shows the friction and wear coefficient curves of coatings obtained at different welding currents. It can be seen that, at the beginning of the friction and wear test, the wear coefficient of the coating increased rapidly and reached a small step at 200 s. Thereafter, the wear coefficient continued to increase, corresponding to the running-in stage. Compared with the friction coefficients of coatings produced at welding currents of 140 A and 180 A, that of the coating produced at 160 A is lower, reaching about 0.25 in the stable wear stage. The wear rate (\( W_s \)) is calculated according to the following formula:

\[
W_s = \frac{W_{\text{lost}}}{P \cdot L}
\]  

Therefore, \( W_s \) represents wear rate, \( W_{\text{lost}} \), \( P \), and \( L \) represent wear weight loss, load, and wear length respectively, and the frictional wear of 5 mm travel distance. The wear rate and wear weight loss are positively dependent, whereas the lower the wear coefficient of the material, the smaller the wear weight loss, which means superior friction and wear resistance. As shown in figure 6(b), the wear rate of the coating is the lowest when compared to 140 A and 180 A at the welding current of 160 A for the same time. The results seem to indicate that WC was the main phase in the coating obtained at 160 A and that \( W_2C \) existed in the coating as a secondary phase, enhancing the binding energy between the WC particles and the Ni-based, providing strength, and
contributing to the wear resistance of the coating substrate. Thus, the matrix was further enhanced by secondary carbides, which also reduced deformation [43–46].

To further verify the above conclusions, the surface morphology of the material after wear was observed by SEM. Additionally, it can be seen in figures 7(a) and (c) that the W2C particles constituted a strengthening phase in the material, having a hardness much greater than that of the Ni-base. Therefore, when an indenter cuts through W2C particles, small particles are broken, and large particles are directly separated from the matrix in which they are embedded to form hard abrasive particles. As a result, there are a lot of holes and cracks on the surface of the coating, accelerating the wear of the material surface. As shown in figures 7(b) and (d), dispersion of the W2C reinforcing phase, with small particle size and uniform distribution, makes the wear trace shallow and leads to a smoother spread zone. The results show that when the welding current is 160 A and the particles are worn, W2C enhances the bonding strength between the Ni matrix and WC. With W2C embedded in the matrix, the WC particles are less likely to fall away, thus improving the wear resistance of the coating [47–51].

4. Conclusions

Based on experimental results and discussion, the following conclusions were summarized as follows:

(1) W2C particles exist in the nickel-based molten pool as the second phase. The length and content of WC particles distributed in the acicular structure around WC particles vary with the current.

(2) The surfacing layer is mainly composed of Fe0.64Ni0.36 phase, WC, W2C, and free C, and each element has different degree of diffusion phenomenon. At a temperature above 2615 K, the tungsten carbide particles melt at high temperature and undergo metallurgical reaction, that is, 2WC = W2C + C, as the temperature drops. When the temperature is lower than 1690 K, W2C begins to change into the WC phase again. The hardness and wear resistance of the coatings are significantly improved under the combined action of the heterotopic and in situ reinforcers.

(3) W2C needle-like particles as an intermediate transition phase reduces the stress between WC and nickel substrate, and the good bond strength and smooth surface of the substrate reduces the porosity and makes the abrasion marks shallow, which greatly improves the friction and wear performance of the material.
(4) The thermal expansion coefficient of each phase at the interface shows that the interfacial transition phase $W_2C$ helps to regulate the difference in thermophysical properties between the body Ni and the reinforcing particles WC, thus slowing down the generation of thermal cracks at the junction of the body Ni and the reinforcing particles.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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References

[1] Sundaramoorthy R, Tong S X, Parshok D and Subramanian C 2017 Effect of matrix chemistry and wc types on the performance of ni-wc based mmc overlays by plasma transferred arc (pta) welding Wear 376 1727
[2] Zhang Z Q, Wang H D, Xu B S and Zhang G S 2015 Investigation on influence of WC–Ni addition on rolling contact fatigue behavior of plasma sprayed Ni-based alloy coating Tribol. Int. 90 509–18
[3] Hu D, Liu Y, Chen H, Liu J, Wang M and Deng L 2021 Microstructure and properties of Ta-reinforced NiCuBSi + WC composite coating deposited on 5Cr5MoSiV1 steel substrate by laser cladding Opt. Laser Technol. 142 107210
[4] Zhang Y, Lou L, Xu Q, Li Y, Li C and Li C 2020 Microstructure and wear resistance of Ni-based WC coating by ultra-high speed laser cladding Acta Metall. Sin. 56 1530–40
[5] Huang X, Zhang J, Cheng Y, Chen C, Lian G, Jiang J and Zhou M 2021 Effect of h-BN addition on the microstructure characteristics, residual stress and tribological behavior of WC-reinforced Ni-based composite coatings Surf. Coat. Tech. 405 126534
[6] Zhou S, Zeng X, Hu Q and Huang Y 2008 Analysis of crack behavior for Ni-based WC composite coatings by laser cladding and crack-free realization Appl. Surf. Sci. 255 1646–53
[7] Zhao S, Yang L, Huang Y and Xu K 2020 Enrichment of in situ synthesized WC by partial dissolution of ex situ eutectoid-structured WC/W2C particle in the coatings produced by laser hot-wire deposition Mater. Lett. 281 126841
[8] Alidokht S A and Chromik R R 2021 Sliding wear behavior of cold-sprayed Ni-WC composite coatings: Influence OF WC content Wear 477 203792
[9] Tillmann W, Hagen L and Kokali D 2017 Spray characteristics and tribo-mechanical properties of high-velocity arc-sprayed WC-W2C iron-based coatings J. Therm. Spray Technol. 26 1685–700
[10] More S R, Bhat D V and Menghani J V 2017 Resent research status on laser cladding as erosion resistance technique—an overview Mater. Today Proc. 4 9902–8
[11] Lin C M 2015 Functional composite metal for WC-dispersed 304L stainless steel matrix composite with alloying by direct laser: Microstructure hardness and fracture toughness Vacuum 121 96–104
[12] Deng D W, Xia H F and Ge Y L 2013 Influence of welding currents on microstructure and microhardness of Ni45 alloy reinforced with spherical tungsten carbides (40 mass%) by plasma transferred arc welding Mater. Trans. 54 2144–50
[13] Iizuka T, Kita H, Hirai T and Osumi K 2004 Tribological behavior of WC nano-particle reinforced Si3N4 matrix composite wear 376 1727
[14] Karmarkar R, Maji P and Ghosh S K 2021 A review on the nickel based metal matrix composite coating Surf. Coat. Tech. 420 127341
[15] Xiao Q, Sun W L, Yang K X, Xing X F and Lu J 2021 Wear mechanisms and micro-evaluation on WC particles investigation of wc-fe composite coatings fabricated by laser cladding Surf. Coat. Tech. 420 127341
[16] Kalyanakar V and Bhoskar A 2021 Influence of torch oscillation on the microstructure of Colmonoy 6 overlay deposition on SS304 substrate with PTA welding process Metall. Res. Technol. 118 4
[17] Wang X, Rong J, Yao Y, Zhang Y, Zong Y, Feng J and Zhan Z 2018 La doping inhibits stress production at the grain boundaries in Ni-WC-J. Alloys. Compd. 733 688–94
[18] Zhang M, Li M, Chi J, Wang S, Yang S, Yang J and Wei Y 2019 Effect of Ti on microstructure characteristics, carbide precipitation mechanism and tribological behavior of different WC types reinforced Ni-based gradient coating Surf. Coat. Tech. 374 645–55
[19] Xie G, Song X, Zhang D, Wu Y and Lin P 2010 Microstructure and corrosion properties of thick WC composite coating formed by plasma cladding Appl. Surf. Sci. 256 6354–8
[20] Liu T, Chang M, Cheng X, Zeng X, Shao H and Liu F 2020 Characteristics of WC reinforced Ni-based alloy coatings prepared by PTA + PMI method Surf. Coat. Tech. 383 125232
[21] Wu Z, Pan M, Zhan Y, Shu S, Xiong L and Li Z 2021 The bonding characteristics of the Cu (111)/WC (0001) interface: an insight from first-principle calculations Vacuum 191 110218
[22] Li X, Zhang X, Qin J, Zhang S, Ning J, Jing R and Liu R 2014 First-principles calculations of structural stability and mechanical properties of tungsten carbide under high pressure J. Phys. Chem. Solids75 1234–9
[23] Dang D Y, Shi L Y, Fan J L and Gong H R 2021 First-principles study of W–TiC interface cohesion Surf. Coat. Tech. 276 602–5
[24] Rao X, Lou Y, Zhou Y, Zhang J and Zhong S 2021 First-principles insights into ammonia decomposition on WC (0001) surface terminated by W and C Appl. Surf. Sci. 566 150635
[25] Wang H L, Yang J J, Zhao Y J and Du J 2015 First-principles study of Mg/Al,MgC heterogeneous nucleation interfaces Appl. Surf. Sci. 355 1091–7
[26] Guo C, Chen J, Zhou J, Zhao J, Wang L, Yu Y and Zhou H 2012 Effects of WC–Ni content on microstructure and wear resistance of laser cladding Ni-based alloys coating Surf. Coat. Tech. 206 2064–71
[27] Li Z, Wei H, Shan Q, Jing J, Zhou Y, Rao R and Feng J 2016 Formation mechanism and stability of the phase in the interface of tungsten carbide particles reinforced iron matrix composites: First principles calculations and experiments J. Mater. Res. 31 2376–83
Günther K and Bergmann J P 2018 Understanding the dissolution mechanism of fused tungsten carbides in Ni-based alloys: an experimental approach Mater. Res. Express 44 43 42 41 40 39 38
Wu P, Du H M, Chen X L, Li Z Q, Bai H L and Jiang E Y 2004 In situ flame sprayed and fused Ni-based coatings Surf. Coat. Tech. 217 208 142 749 10–22
Erfanmamesh M, Abdollahi-Pour H, Mohammadzadeh-Sennani H and Shoja-Razavi R 2018 Kinetics and oxidation behavior of laser clad WC-Co and Ni/ WC-Co coatings Ceram. Int. 44 12805–14
Liao M, Liu Y, Min L, Lai Z, Han T, Yang D and Zhu J 2018 Alloying effect on phase stability, elastic and thermodynamic properties of Nb-Ti-V-Zr high entropy alloy Intermetallics 101 152–64
Li X, Zhang X, Qin J, Zhang S, Ning J, Jing R and Liu R 2014 First-principles calculations of structural stability and mechanical properties of tungsten carbide under high pressure J. Phys. Chem. Solids 75 1234–9
Weng Z, Wang A, Wu X, Wang Y and Yang Z 2016 Wear resistance of diode laser-clad Ni/ WC composite coatings at different temperatures Surf. Coat. Tech. 304 283–92
Przybyłowicz J and Kusiński J 2001 Structure of laser cladded tungsten carbide composite coatings J. Mater. Process. Tech. 109 154–60
Ying W E I, Wei X S, Bo C H E N, Zuo J Y and Jun S H E N 2018 Parameter optimization for tungsten carbide/ Ni-based composite coating deposited by plasma transferred arc hardfacing T. Nonfer Metal. Soc. 28 2511–9
Katsich C and Badisch E 2011 Effect of carbide degradation in a Ni-based hardfacing under abrasive and combined impact/ abrasive conditions Surf. Coat. Tech. 206 1062–8
Sui Y et al 2018 Microstructure and wear resistance of laser-cladded Ni-based composite coatings on downhole tools J. Mater. Process. Technol. 252 217–24
Benza L, Caron N and Raquet O 2016 Tribological behavior of a Ni matrix hybrid nanocomposite reinforced by titanium carbide nanoparticles during electro-codeposition RSC Adv. 6 59775–83
Dash T and Nayak B B 2019 Tungsten carbide–Titanium carbide composite preparation by arc plasma melting and its characterization Ceram. Int. 45 4771–80
Myalska H, Swadzha R, Rozmus R, Moskal G, Wiedermann J and Szymański K 2017 STEM analysis of WC-Co coatings modified by nano-sized TiC and nano-sized WC addition Surf. Coat. Tech. 318 279–87
Wu P, Du H M, Chen X L, Li Z Q, Bai H L and Jiang E Y 2004 Influence of WC particle behavior on the wear resistance properties of Ni–WC composite coatings Wear 257 142–7
Shu D, Li Z, Zhang K, Yao C, Li D and Dai Z 2017 In situ synthesized high volume fraction WC reinforced Ni-based coating by laser cladding Mater. Lett. 195 178–81
Günther K and Bergmann J P 2018 Understanding the dissolution mechanism of fused tungsten carbides in Ni-based alloys: an experimental approach Mater. Lett. 213 253–6