Friction and Wear Properties of Quasi-Surface Textured Nickel-Based Composite Coatings (Postprint)

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Abstract

Nickel-based alloy (Ni0) composite coatings with a texture-like cross-sectional morphology were prepared on low-carbon steel surfaces via vacuum cladding method with additions of WC particles at a mass fraction of 20% and graphite particles at 6%. The microstructural morphology, formation mechanism, phase composition, and friction and wear performance under dry friction conditions of the composite coatings were investigated and compared with three other coatings: nickel-based alloy (Ni0), tungsten carbide reinforced nickel-based alloy (Ni0+20%WC), and graphite modified nickel-based alloy (Ni0+6% graphite). The results show that WC exhibits a discontinuous three-dimensional network distribution in the nickel-based alloy matrix. The nickel-based alloy is mainly composed of the matrix phase γ-Ni, chromium compound hard phases CrB, Cr7C3, Cr23C6, and eutectic phases Ni3B, Ni3Si. The individual addition of either WC or graphite can improve the friction and wear performance of the composite coatings. The friction and wear performance of the composite cladding layer with texture-like structure is superior to that of composite cladding layers with the same composition but with hard particles individually dispersed. Under the combined influence of the texture-like morphological structure composed of WC and nickel-based alloy matrix and the graphite lubricating phase, the wear resistance of the composite coating is improved by approximately 9.6 times compared with the single nickel-based alloy coating.

Full Text

Wear Resistance of a Texture-like Nickel-based Composite Coating

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Abstract

A nickel-based (Ni0) composite coating reinforced with 20 wt% WC and 6 wt% graphite particles was fabricated on a low-carbon steel substrate using vacuum cladding technology, resulting in a texture-like cross-sectional morphology. The microstructure, formation mechanism, phase composition, and dry friction wear properties of the composite coating were investigated and compared with three other coatings: pure nickel-based alloy (Ni0), tungsten carbide-reinforced nickel-based alloy (Ni0+20%WC), and graphite-modified nickel-based alloy (Ni0+6% graphite). The results demonstrate that WC particles formed a discontinuous three-dimensional network distribution within the nickel-based alloy matrix. The nickel-based alloy consisted primarily of the γ-Ni matrix phase, chromium compound hard phases (CrB, Cr7C3, Cr23C6), and eutectic phases (Ni3B, Ni3Si). Both individual additions of WC and graphite improved the friction and wear properties of the composite coatings, with the texture-like composite cladding exhibiting superior tribological performance compared to coatings with individually dispersed hard particles. Under the combined influence of the texture-like structure composed of WC and the nickel-based matrix along with the graphite lubricating phase, the wear resistance of the composite coating was enhanced by approximately 9.6 times compared to the pure nickel-based alloy coating.

Keywords: materials failure and protection, nickel-based composite coating, vacuum cladding, texture-like structure, WC

Introduction

Metal matrix ceramic composites exhibit high resistance to various forms of wear by combining the advantages of hard particles and a tough matrix, which reduces stress through plastic deformation [1]. Tungsten carbide-reinforced nickel-based alloys are widely used in metal matrix ceramic composites to extend the service life of mechanical equipment operating under wear, corrosion, and impact conditions, such as cutting tools, molds, and mining equipment [2,3]. Compared with other carbide phases, tungsten carbide possesses numerous excellent properties, including high hardness, certain plasticity, and good wettability, making it widely applicable in situations where single nickel-based alloys cannot meet requirements [4,5].

For materials operating under oil-free or low-oil lubrication conditions, the addition of solid lubricants can improve wear resistance [6-8]. Graphite crystals with a layered structure undergo delamination failure under tangential friction forces, forming a lubricating film on the friction surface that reduces friction. Research has shown that preparing specific micro-textures on material surfaces can improve friction and wear performance [9]. For example, Hu Tianchang et al. [10,11] used laser texturing on 45# steel surfaces, achieving reduced friction coefficients and wear rates.

Numerous studies have explored tungsten carbide-reinforced nickel-based alloys and graphite-modified nickel-based self-lubricating materials. This paper employs vacuum cladding technology to prepare nickel-based alloy composite coatings on Q235 steel surfaces with two-dimensional surface texturing and three-dimensional network distribution of tungsten carbide, investigating their friction and wear performance and the influence of graphite on tribological properties.

Experimental Methods

The substrate material used was Q235 steel plate with dimensions of 50 mm × 50 mm × 10 mm. The chemical composition of the nickel-based alloy powder (Ni0) used for cladding layer preparation was (wt%): 0.7C, 4.6Si, 17Cr, 3Fe, balance Ni. The nickel-based alloy powder particles exhibited spherical morphology with sizes ranging from 48–106 μm. The reinforcement particles were WC ceramic powder with particle sizes less than 18 μm, while the solid lubricant phase was nickel-coated graphite particles with sizes of 45–105 μm.

Composite coatings were prepared using vacuum cladding technology following powder metallurgy methods. Three types of composite powders were mixed uniformly: 6 wt% graphite (abbreviated as G) + balance Ni0, 20 wt% WC + balance Ni0, and 6 wt% graphite (G) + 20 wt% WC + balance Ni0. The nickel-based alloy powder and the three composite powders were then coated onto the surface of the substrate after rust and oil removal using a binder (coating thickness approximately 2 mm). For samples with WC addition, a Ni0 transition layer approximately 1 mm thick was applied. The prepared specimens were dried in a muffle furnace (100°C × 2 h) to produce preforms. The preforms were then sintered in a zt-18-22 vacuum carbon tube furnace (1050°C × 30 min) to produce test samples. The heating rate was 60°C/min, and samples were air-cooled after furnace cooling to below 150°C.

Friction and wear tests were conducted using an EMM-1 friction tester with a pin-on-disk contact configuration. The disk was made of quenched and tempered GCr15 steel (0.8C, 0.11Si, 0.2Mn, 1.2Cr, balance Fe) with a surface roughness Ra of 0.35 m, hardness of 55–60 HRC, diameter of 50 mm, and thickness of 5 mm. The pins were machined from samples with the four different coatings, with a diameter of 5 mm, length of approximately 12 mm, and surface roughness Ra of 0.28–0.50 m. Dry friction experiments were performed in ambient air at room temperature under a load of 15 N, friction frequency of 30 Hz, sliding speed of approximately 3.36 m/s, and test duration of 60 min. The friction coefficient was automatically recorded by computer. Since the wear scar on the pin was approximately circular, the wear scar diameter d (mm) was measured using scanning electron microscopy, and the spherical cap volume was calculated using the formula $\Delta V = \pi d^4/64r$ (where ΔV is wear volume and r is the hemispherical pin diameter). The wear rate was calculated using the formula $\Delta V/F \cdot S$ (where F is load and S is sliding distance). The weight loss of the disk counterpart was measured using an analytical balance with 0.1 mg precision. All friction coefficients and wear rates reported in this paper represent the average of three repeated tests.

The microstructure and worn surface morphologies of the coatings were observed using scanning electron microscopy (SEM). Phase composition was analyzed using X-ray diffraction (XRD), and elemental distribution was examined using energy-dispersive spectroscopy (EDS).

2.1 Coating Composition and Microstructure

Figure 1 [Figure 1: see original paper] presents the XRD pattern of the tungsten carbide-reinforced nickel-based alloy composite coating. In addition to WC, the coating consists primarily of the matrix phase γ-Ni, chromium compound hard phases CrB, Cr7C3, and Cr23C6, and eutectic phases Ni3B and Ni3Si. XRD analysis results for other samples were essentially consistent with these findings, apart from the added phases.

Figure 2 [Figure 2: see original paper] shows SEM micrographs of the four vacuum cladding coatings with different compositions. Figure 2a displays the secondary electron image of the coating composed entirely of Ni-based alloy. Numerous granular or elongated phases are dispersed in the lighter-colored alloy matrix. Based on XRD analysis, the light-colored matrix is primarily the γ-

Ni phase, while the granular or strip-shaped phases are chromium carbides or borides. These carbide and boride phases possess higher hardness than the matrix phase and contribute to improving the hardness and wear resistance of the nickel-based alloy to some extent [12]. Figure 2b presents the backscattered electron image of the nickel-based alloy composite coating after graphite particle addition, showing discrete distribution of graphite particles in the coating. Local magnified microstructure reveals that the particles distributed in the matrix are chromium compound hard phases, while the black lamellar structure is the nickel-based eutectic phase [12].

Figures 2c and 2d show backscattered electron images of Ni0+WC and Ni0+WC+G alloy microstructures, respectively. The bright white particles with network distribution are WC particles, whose angular edges remain relatively intact. This indicates that no significant burnout or dissolution of tungsten carbide occurred during coating formation, preserving the original properties of WC particles. The nickel-based powder particles, serving as the matrix phase in the composite coating, essentially maintained their original spherical shape after sintering, as shown in the elliptical marked regions in Figure 2c. The nickel-based alloy particles melted and fused with each other during coating formation, precipitating hard phases (carbides or borides CrB, Cr7C3, Cr23C6) and eutectic phases (Ni + Ni3B or Ni+Ni3Si) during cooling, as shown in the elliptical regions. The dark gray strip-like material, visible at higher magnification in Figure 2b, consists of hard phases and lamellar eutectic phases. Figure 2d shows uniformly dispersed WC and graphite. WC formed a special 3D network in the composite coating. Each cross-section of the coating consisted of the nickel-based alloy matrix and a "WC network" with approximately circular "mesh holes," which were the fused nickel-based alloy regions. Further observation reveals that the WC network was not continuous; rather, gaps were maintained between WC particles in relatively concentrated distribution areas. These gaps represent the regions where nickel-based alloy fused and connected. This structure prevents the significant strength reduction caused by continuous brittle phase precipitation at grain boundaries, similar to that occurring in steel. This WC distribution gives any cross-section of the coating a texture-like morphology, which can significantly improve friction and wear performance [11].

2.2 Formation Mechanism of Texture-like Structure

The attainment of texture-like structure depends on the selection of raw powders for surface cladding, the adopted process method, and control of process parameters such as heating temperature and holding time during preparation. This study combined relatively large nickel-based alloy powder particles with relatively small WC powder particles. After uniform mixing, the small WC particles were distributed in the gaps between the spherical nickel-based alloy particles, forming a uniform alternating distribution. Another important factor for the texture-like morphology is the appropriate combination of process method and parameters. Compared with other surface coating technologies such as laser cladding, plasma cladding, or surface welding, vacuum cladding technology has lower energy density. The uniform and stable heat input produces minimal stirring effect on the liquid phase, preventing large-scale relative displacement within the cladding layer during formation. The melting point of the nickel-based alloy powder used in this study was (1000$±$30)°C, and WC addition slightly changed the overall melting point of the composite preform layer. The viscosity of commonly used metallic materials in the liquid state decreases with increasing temperature [13]. Therefore, the molten nickel-based alloy at the maximum heating temperature of 1050°C had relatively high viscosity. Under appropriate holding time conditions, no large-scale macroscopic relative flow occurred during composite coating formation, ensuring the distribution of the discontinuous network hard phase, as confirmed by the microstructural morphology in Figures 2c and 2d.

During the heating stage of coating preparation, the nickel-based alloy particles in the preform first began to soften and melt at the edges and particle contact points/surfaces. With further temperature increase, melting necks formed at contact points or surfaces and deepened during the holding stage. The capillary siphoning effect in capillaries formed between particles caused the molten nickel-based metal liquid to flow within these capillaries. During the holding process, the liquid phase gradually increased, and the liquid nickel-based alloy achieved complete fusion between WC particles. Due to the irregular particle sizes, the capillary diameters also varied. Consequently, WC particles continuously adjusted their positions and orientations during the flow of molten metal. Tungsten carbide particles experienced micro-displacement due to interfacial tension during regional viscous flow of the molten metal, creating nickel-based alloy regions with certain thickness gaps between WC particles. Macroscopically, the nickel-based alloy particles melted and fused with adjacent particles without displacement, maintaining an approximately spherical shape after cooling and crystallization. The central regions of the melted nickel-based alloy particles precipitated carbides, borides, and eutectic phases during holding and cooling, as shown in Figures 2b and 2c. During sintering, WC particles were wetted by the metal liquid and remained in a near-floating state, moving under the action of interfacial tension and liquid metal. They gradually adjusted their orientation under the combined action of capillary forces formed between WC particles and the inflowing liquid metal, forming a dense composite coating. Appropriate holding time avoided extensive dissolution, decomposition, or connection of WC. Under the combined effects of these conditions, a composite coating with network texture morphology in cross-section was ultimately formed.

2.3 Friction and Wear Properties of Coatings

The four nickel-based alloy and composite coatings—Ni0, Ni0+G, Ni0+WC, and Ni0+WC+G—were designated as Samples 1, 2, 3, and 4, respectively. Figure 3 [Figure 3: see original paper] presents the wear rates, friction coefficients, and counterface wear for the four alloy coatings under identical dry friction conditions. Figure 3a shows the variation curves of friction coefficient and wear rate for the four different coatings. The wear resistance of the Ni/WC composite cladding was nearly 6 times higher than that of the nickel-based alloy cladding, while the Ni/WC/G composite cladding showed an 8.4-fold improvement over the Ni/G composite cladding. These results indicate that WC addition significantly reduced the wear rate (i.e., substantially improved wear resistance), though it increased the friction coefficient to varying degrees. The friction coefficient of the Ni/WC composite cladding increased by 22.8% compared to the nickel-based alloy cladding, while that of the Ni/WC/G composite cladding increased by 19.2% compared to the Ni/G composite cladding. The Ni/G composite cladding exhibited a 13% improvement in wear resistance over the nickel-based alloy cladding, and the Ni/WC/G composite cladding showed a 52% improvement over the Ni/WC composite cladding. This demonstrates that graphite addition reduced both the friction coefficient and wear rate of the alloy or composite cladding, proving beneficial for improving the tribological performance of nickel-based alloy claddings. The composite cladding with simultaneous WC and graphite addition showed a 9.6-fold improvement in wear resistance over the pure nickel-based alloy coating, with a 10.1% increase in friction coefficient. This indicates that during the friction and wear process of composite claddings, the reinforcement effect of WC played the primary role in reducing wear, while the combination of reinforcement phase and graphite lubrication provided optimal anti-wear and friction-reducing effects.

The wear loss variation of the Gr15 steel disk (Figure 3b) shows that the counterface wear for the Ni/WC composite cladding increased by 180% compared to the nickel-based alloy cladding, while the Ni/WC/G composite cladding counterface wear increased by 128% compared to the Ni/G composite cladding, indicating that WC addition accelerated counterface wear. In contrast, the Ni/G composite cladding reduced counterface wear by 22% compared to the nickel-based alloy cladding, and the Ni/WC/G composite cladding reduced counterface wear by 36.4% compared to the Ni/WC composite cladding, demonstrating that graphite particle addition significantly reduced counterface wear. For composite claddings containing WC, graphite addition substantially reduced wear on the counterpart. Combined analysis of wear rate and friction coefficient results indicates that simultaneous WC and graphite addition greatly improved the anti-wear and friction-reducing performance of the composite cladding while benefiting the reduction of counterface wear.

Figure 4 [Figure 4: see original paper] shows SEM micrographs of the worn surfaces of the four claddings. Figure 4a reveals that the worn surface of the nickel-based alloy cladding exhibited extensive large-area spalling pits with small amounts of wear debris retained within the pits, along with numerous shallow plowing grooves along the sliding direction, characteristic of fatigue wear and abrasive wear. Figure 4b shows that the worn surface of the Ni/G composite cladding was relatively smooth compared to the nickel-based alloy cladding, with small amounts of wear debris and slight wear marks. Bright wear debris adhesion was observed, concentrated primarily in relatively shallow wear mark pits (elliptical regions in the figure). Table 1 presents EDS compositional analysis results of the wear debris. Besides Ni, Cr, and Si from the nickel-based alloy and C from the solid lubricant phase, the debris contained substantial O and Fe elements. These results indicate that the wear debris comprised the main elements from both friction pair materials. Additionally, since friction occurred in atmospheric environment, the debris contained significant oxygen. This suggests that the wear debris consisted of oxides of Ni, Cr, Fe and other main elements, as well as graphite flakes stripped from the graphite phase under frictional shear stress and mixed with the debris. During friction, interfacial temperature increased substantially, with flash temperatures at the friction interface potentially reaching the metal melting point [14]. The elevated temperature caused Ni, Cr, Fe, and other elements to combine with atmospheric oxygen to form corresponding oxides, with iron oxides also providing some lubricating effect [15].

Figure 4c shows the worn surface morphology of the Ni/WC composite cladding, revealing continuous dense plowing grooves and substantial bright wear debris concentrated primarily in regions surrounding WC particles. The texture-like network morphology of WC remained visible on the worn surface (dashed elliptical line in the figure), with WC particles distributed along its outer edge. Figure 4d presents the worn surface morphology of Ni0+WC+G. Compared to the Ni/WC composite cladding, the worn surface was relatively smooth with no obvious plowing grooves after graphite addition. Wear debris spread more uniformly on the worn surface, with dense and smooth debris surfaces (large smooth area marked A in the white ellipse in Figure 4d). In other regions, smaller dense smooth areas gradually formed (small white elliptical regions). Figure 5 [Figure 5: see original paper] shows magnified morphology of the Ni/WC/G composite cladding worn surface and EDS carbon element distribution results. During wear, WC gradually became a protruding network supporting the load, with wear debris accumulating around it (Figures 5a and 5b). Figure 5b shows a local magnified morphology of the worn surface with wear debris, revealing the network distribution of bright WC particles. Figure 5c presents elemental distribution analysis of the worn surface, showing relatively uniform carbon distribution. The reason is that during wear, after the nickel-based alloy matrix was worn to a certain extent, WC protruded from the base surface to provide primary wear resistance. The large amount of cutting-generated wear debris accumulated in the adjacent circular nickel-based alloy regions (Figure 5a), protecting the matrix. Meanwhile, as wear debris was continuously expelled during friction, graphite addition reduced adhesion between the debris and Gr15 steel, facilitating its stable attachment within the circular structures formed by WC and slowing its loss rate. This explains why Sample 4 exhibited lower friction coefficient and wear rate than Sample 3.

2.4 Wear Mechanism of Claddings

During wear of the nickel-based alloy cladding, the high hardness of the counterface disk caused fatigue-induced spalling pits and plowing grooves along the sliding direction on the contact surface under normal load pressure and shear stress (Figure 4a). After graphite addition to the cladding, the worn surface was generally smoother with small amounts of attached wear debris. During friction, graphite particles fractured into layered flakes under shear stress and mixed with wear debris, gradually spreading on the friction surface to form a relatively flat and smooth surface (Figure 4b), reducing shear stress in the tangential direction of the friction contact interface and simultaneously decreasing both friction coefficient and wear rate. WC particle addition to the nickel-based alloy substantially reduced wear rate because the hard particles increased composite cladding hardness. According to Archard’ s law ($Q = KLN/H$, where Q is wear rate, N is load, L is sliding distance, H is surface hardness, and K is friction coefficient), wear rate is inversely proportional to hardness. Therefore, increased hardness reduces wear rate. The addition of WC particles and formation of hard phase particles significantly increased composite layer hardness, thereby improving cladding wear resistance [16]. The WC particles in this cladding exhibited a non-directly-connected network distribution, forming a texture-like structure. When hard phases are individually dispersed, wear debris formed during friction is easily expelled from the friction contact interface under shear stress, and WC particles providing load support are fewer on the friction contact plane, making them susceptible to crushing and fragmentation under vertical load, subsequently forming three-body abrasive wear.

The wear rate of the Ni/WC composite cladding was 5.52×10^{-8} g/(N • M) [17], while that of the texture-like Ni/WC composite cladding was 6.69×10^{-9} g/(N • M). When WC particles formed a texture-like structure, they created a network load support on the friction contact plane. Under these conditions, the load borne by individual particles decreased substantially, and the generated wear debris was easily captured and even gradually filled the low-lying areas around WC particles. Since oxides of main elements (Ni, Fe) formed in atmospheric environment and these oxides provide certain friction-reducing effects [15], the formation of texture-like network structure significantly improved wear resistance. When both WC and graphite particles were added to the cladding, both wear rate and friction coefficient decreased. As friction progressed, the subsurface of the contact region deformed, and graphite particles in the cladding fractured into layered flakes. The stripped graphite particles mixed with wear debris and were squeezed into the network formed by WC particles under frictional shear stress. Graphite and oxides formed a relatively dense debris layer with friction-reducing effects, while hard particles and the WC network provided load support. The wear rate of the texture-like Ni/WC/G composite cladding was 4.44×10^{-9} g/(N·M), while that of the non-texture-like Ni/WC/G composite cladding was 1.92×10^{-8} g/(N·M) [17]. This demonstrates that texture-like structures formed by hard phases or hard particles can significantly improve the friction and wear performance of cladding or coating materials.

Conclusions

1. Nickel-based composite coatings prepared by vacuum cladding technology exhibited dense microstructure. The Ni/WC composite cladding and Ni/WC/G composite cladding featured texture-like structural characteristics. The phase composition consisted primarily of the nickel-based solid solution γ-phase, hard precipitated phases CrB, Cr7C3, Cr23C6, and eutectic phases Ni3B, Ni3Si. The composite claddings also contained WC or graphite, with no decomposition of WC observed.
2. The texture-like structure formed by hard phase WC particles significantly improved the friction and wear performance of the cladding. Under identical conditions, the wear rate of the texture-like composite cladding was lower than that of the Ni/WC composite cladding with individually dispersed WC particles.
3. The effect of WC addition in reducing wear rate was superior to that of graphite particles, while graphite particle addition significantly reduced the friction coefficient. Compared with the other three claddings, the texture-like composite cladding with simultaneous WC and graphite addition exhibited the best anti-friction and anti-wear performance.

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