

Research on the Wear Resistance of Laser-Clad JG-2/cBN Composite Coatings on GH4169 Nickel-Based Alloy

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ABSTRACT

To enhance the surface wear resistance of GH4169 nickel-based superalloy components under extreme service conditions, this study investigates a laser-clad JG-2/cBN composite coating. The composite coating was fabricated on the GH4169 substrate using a high-power fiber laser with optimized processing parameters (laser power: 1.5 kW, scanning speed: 5 mm/s, powder feed rate: 15 g/min). The JG-2 nickel-based alloy powder was mechanically mixed with cubic boron nitride (cBN) particles at a 1:1 volume ratio as the cladding material, with a pure JG-2 coating prepared under identical conditions as the control group. The microstructure, phase composition, microhardness, and tribological properties of the coatings were systematically characterized. Friction and wear tests were conducted using a ball-on-disc configuration under a 50 N load at room temperature for 60 minutes. Three-dimensional laser confocal microscopy, wear volume measurement, and two-dimensional profilometry were employed to evaluate wear track morphology and wear mechanisms. Results demonstrate that the JG-2/cBN composite coating exhibits superior tribological performance compared to the monolithic JG-2 coating. The friction coefficient of the composite coating remained stable between 0.25 and 0.30 throughout the test, significantly lower than that of the JG-2 coating (approaching 0.9 with severe fluctuations). The maximum wear depth decreased from approximately 97 μm (JG-2 coating) to 20 μm (composite coating), while the wear volume was reduced by approximately 80.1% (from 188,881,542 μm^3 to 37,626,995 μm^3). Two-dimensional wear scar profiles revealed shallower and narrower grooves with smoother contours for the composite coating, indicating suppressed plastic deformation and material detachment. The incorporation of cBN hard particles enhances the load-bearing capacity, micro-cutting resistance, and interfacial stability of the coating, effectively mitigating adhesive wear, plowing, and oxidative wear mechanisms. This study provides a theoretical foundation and experimental reference for surface strengthening and remanufacturing of critical nickel-based alloy components, demonstrating the potential of cBN-reinforced composite coatings for demanding tribological applications.

KEYWORDS

Laser Cladding; Cubic Boron Nitride (cBN); Wear Resistance; Friction Behavior.

1. INTRODUCTION

Nickel-based alloys are widely used in aerospace, energy power generation, petrochemical, and high-end equipment manufacturing due to their excellent high-temperature strength, oxidation resistance, corrosion resistance, and favorable comprehensive mechanical properties. However, under complex service conditions involving heavy loads, impacts, friction, and high temperatures, material surfaces often first exhibit failure mechanisms such as abrasive wear, adhesive wear, and oxidative wear. This leads to dimensional instability of components, reduced service life, and may even induce premature failure of critical structures. Therefore, enhancing the surface wear resistance of nickel-based alloys

while preserving their excellent overall properties has become a significant research focus in surface engineering and remanufacturing[1-3].

Laser cladding, as a significant surface modification technique, utilizes a high-energy laser beam as a heat source to simultaneously melt and rapidly solidify alloy powder with the substrate surface within an extremely short timeframe. This process forms a reinforced layer on the substrate surface that achieves excellent metallurgical bonding with the substrate. Compared to thermal spraying, surfacing welding, and conventional surface heat treatment, laser cladding offers advantages such as low dilution ratio, minimal heat-affected zone, dense microstructure, and tunable composition. It significantly enhances material surface hardness, wear resistance, and service reliability [4]. Consequently, research on wear-resistant strengthening of nickel-based alloy surfaces through laser cladding holds not only clear engineering application value but also significant theoretical significance.

Currently, to enhance the wear resistance of cladding layers, researchers have conducted extensive studies on both iron-based and nickel-based coating systems. Iron-based coatings typically exhibit higher hardness and superior wear resistance at ambient temperatures. However, under extreme operating conditions such as high temperatures, severe corrosion, and complex loading, their microstructural stability, oxidation resistance, and service reliability remain limited. In contrast, nickel-based alloys offer superior high-temperature stability and environmental adaptability, making them more suitable as surface strengthening materials for extreme service conditions. Existing nickel-based clad layers are primarily based on self-fluxing nickel-based alloys such as NiCrBSi, Ni60, and Ni45. The incorporation of hard ceramic phases like WC, NbC, and TiC enhances coating hardness and load-bearing capacity, thereby improving wear resistance [5-7]. Although such composite coatings achieve satisfactory strengthening effects under conventional operating conditions, they may still face challenges such as agglomeration of reinforcing phases, insufficient interfacial bonding, high crack sensitivity, and inadequate friction stability under high-temperature, heavy-load, and complex friction conditions [8-10]. Consequently, relying solely on traditional hard phase reinforcement struggles to meet the heightened demands for wear resistance and service stability under extreme operating conditions. Cubic boron nitride (cBN), as a typical superhard material, combines high hardness, thermal stability, and excellent chemical inertness, demonstrating significant application potential in high-temperature friction and wear environments. Incorporating cBN into nickel-based laser cladding coatings holds promise for enhancing load-bearing capacity and micro-cutting resistance while further improving high-temperature wear resistance and service reliability.

Based on this, this paper focuses on enhancing the surface wear resistance of nickel-based alloys through laser cladding. By selecting an appropriate nickel-based cladding material system and introducing cBN as a reinforcing phase, combined with key process parameters such as laser power, scanning speed, and powder feed rate, a high-quality composite cladding layer was prepared on the substrate surface. Further investigations, including microstructural observation, phase analysis, microhardness testing, and friction-wear experiments, systematically examined the microstructure characteristics, strengthening mechanisms, and wear behavior of the clad layers. By analyzing wear scar morphology and debris, the primary wear mechanisms under different operating conditions were revealed, and the intrinsic relationship between process parameters, microstructural evolution, and wear resistance was explored. This research provides theoretical foundations and experimental references for surface strengthening and remanufacturing of critical nickel-based alloy components.

2. EXPERIMENTAL PROCEDURE

This experiment utilized nickel-based alloy GH4169 as the substrate material. Specimen dimensions were 30 mm × 30 mm × 10 mm. Surfaces underwent mechanical grinding and ultrasonic cleaning for pretreatment to remove oxide layers and impurities, ensuring sound metallurgical bonding between

the clad layer and substrate. Two types of coatings were prepared using laser cladding: the experimental group featured a composite coating of JG-2 powder and cBN powder (blended uniformly at a 1:1 volume ratio), while the control group utilized a coating of pure JG-2 powder.

Laser cladding employed a high-power fiber laser with a power of 1.5 kW, a scanning speed of 5 mm/s, a powder feed rate of 15 g/min, and a laser spot diameter of 3 mm. Argon gas shielding at a flow rate of 15 L/min was used during the cladding process to minimize oxidation of the molten pool. Both coating types were fabricated using a multi-pass overlapping scan pattern to ensure uniform thickness, approximately 1.2 mm. Post-fabrication surface polishing and stress-relief annealing were performed to eliminate residual stresses and enhance coating stability.

After coating preparation, samples underwent friction and wear performance testing. Tests were conducted at room temperature using a ball-on-disc friction tester with a 6 mm diameter hard steel ball, a load of 50 N, a rotational speed of 200 rpm, and a friction duration of 60 minutes. Changes in the coefficient of friction were recorded, and wear debris samples were collected. The post-friction wear coating surface underwent three-dimensional topography scanning using a laser confocal microscope to obtain parameters such as wear scar depth, volume, and surface roughness. This analysis examined surface damage characteristics under friction-wear conditions for different coatings. By comparing the wear scar morphology and friction performance between the JG-2 single-powder coating and the JG-2+cBN composite coating, the effectiveness of cBN reinforcement in enhancing the wear resistance of nickel-based alloy surfaces can be evaluated.

3. PERFORMANCE TESTING

The friction coefficient curves reveal that T1 coating (JG-2 coating) and T2 coating (JG-2+cBN composite coating) exhibit distinctly different tribological behaviors during friction. The friction coefficient of the T1 coating rises rapidly at the beginning of the test, followed by a sustained overall increase accompanied by significant fluctuations. By 60 minutes, it approaches 0.9, indicating an unstable contact interface during friction, prone to phenomena such as adhesion, plowing, and localized material spalling. In contrast, the friction coefficient of the T2 coating remained significantly lower than that of T1 throughout the test. It started at approximately 0.45, then gradually decreased over time and stabilized between 0.25 and 0.30 with minimal fluctuations. This indicates that the JG-2+cBN composite coating exhibits superior friction stability. This advantage primarily stems from the introduction of cBN as a hard reinforcing phase, which enhances the coating's surface hardness and load-bearing capacity. This reduces surface plastic deformation and adhesive wear during friction, effectively lowering the friction coefficient. Overall, the T2 coating outperforms the T1 coating in both friction coefficient reduction and friction process stability, demonstrating superior wear resistance.

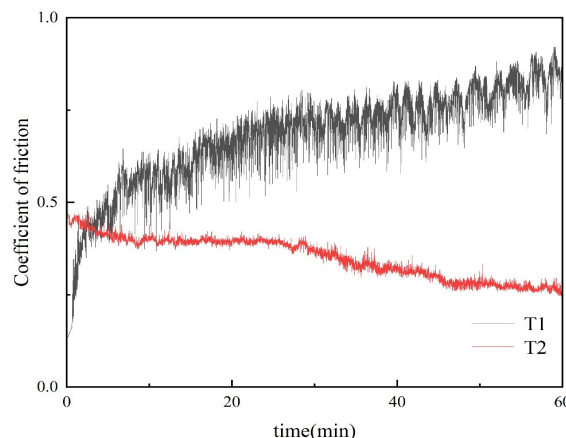


Figure 1. Friction coefficient curve

As shown in the figure, the wear marks on the left JG-2 coating are more pronounced, with a significant variation in surface height. The maximum wear depth reaches approximately 97 μm , exhibiting striated patterns. The surface appears rough, displaying clear signs of plastic flow and micro-crack traces. This indicates that the surface material of the single JG-2 coating is prone to delamination during friction and wear processes, demonstrating relatively limited wear resistance.

In contrast, the wear marks on the JG-2+cBN composite coating on the right side were significantly reduced, with a maximum wear depth of approximately 20 μm . The surface height variation was minimal, the wear marks were smooth, and no obvious cracks or spalling were observed. This indicates that incorporating cBN hard particles into the JG-2 base coating enables the coating surface to more effectively distribute loads during friction, thereby reducing plastic deformation and material detachment. Consequently, the coating's wear resistance is significantly enhanced.

Overall, the results from laser confocal 3D topography scanning indicate that cBN reinforcement significantly improves the surface wear characteristics of the coating, producing smoother wear tracks with shallower depths. This validates the effectiveness of composite reinforcement materials in enhancing the wear resistance of nickel-based alloy surfaces.

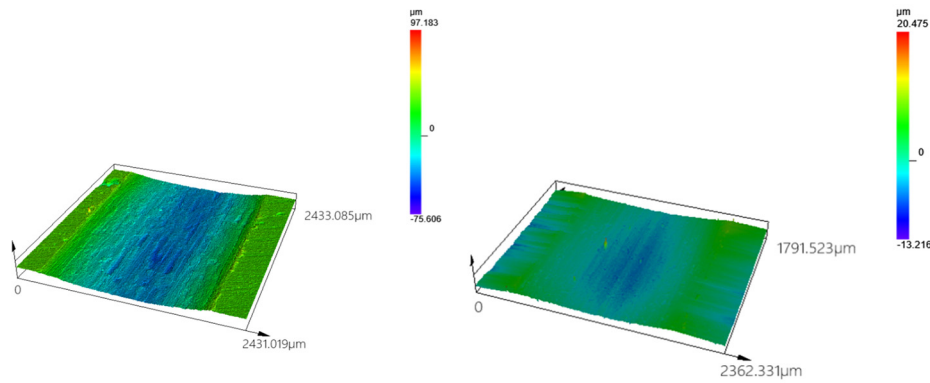


Figure 2. Abrasion Pattern

The wear volume histogram reveals that the wear volume of the T1 coating (JG-2 coating) is 188,881,542 μm^3 , while that of the T2 coating (JG-2+cBN composite coating) is only 37,626,995 μm^3 . Compared to T1, T2 exhibits a significant reduction in wear volume, approximately 80.1%, indicating that the addition of cBN markedly enhances the coating's wear resistance. This demonstrates that the cBN hard reinforcement phase effectively improves the coating surface's load-bearing capacity and resistance to plastic deformation during friction, mitigating material spalling and plowing damage, thereby substantially reducing wear volume. Overall, the JG-2+cBN composite coating exhibits superior wear resistance compared to the standalone JG-2 coating, confirming that incorporating cBN positively enhances the friction and wear performance of laser-clad layers on GH4169 surfaces.

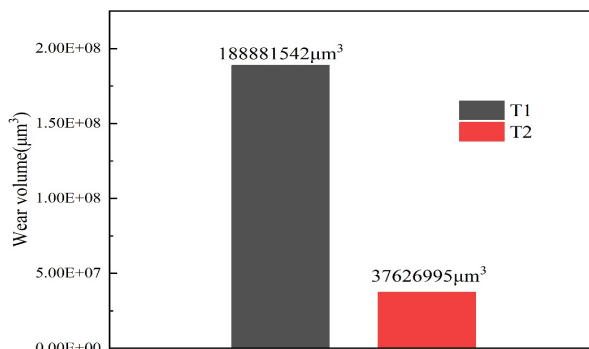


Figure 3. Wear Volume

The two-dimensional contour curves of the wear marks reveal that the wear grooves of the T1 coating (JG-2 coating) are significantly deeper and wider. The overall contour exhibits a pronounced “U”-shaped concavity, with a maximum wear depth reaching approximately 70–75 μm . Additionally, noticeable undulations are present in the central region of the wear marks, indicating severe material removal and localized spalling on the coating surface during friction. In contrast, the wear scar profile of the T2 coating (JG-2+cBN composite coating) is markedly shallower, with a maximum depth of approximately 30–35 μm . The scar width is also relatively smaller, and the overall curve is smoother, exhibiting only minor fluctuations in localized areas. This indicates a lesser degree of surface damage and a more stable wear process. These results demonstrate that incorporating cBN enhances the composite coating's resistance to plastic deformation and load-bearing capacity. This effectively mitigates plowing action and material stripping during friction, significantly reducing both scratch depth and wear severity. Overall, the T2 coating exhibits superior wear resistance compared to the T1 coating, consistent with its lower friction coefficient and reduced wear volume.

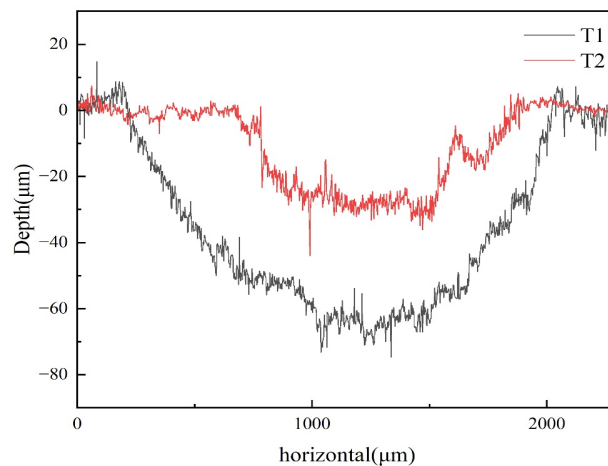


Figure 4. Two-dimensional curve of grinding scar morphology

4. CONCLUSION

This study prepared two distinct nickel-based alloy coatings—JG-2 coating (T1) and JG-2+cBN composite coating (T2)—via laser cladding technology, and systematically investigated their friction and wear properties. Experimental results demonstrate that the JG-2+cBN composite coating exhibits significantly enhanced wear resistance compared to the single JG-2 coating. Specifically: T2 exhibits a markedly lower coefficient of friction than T1, with more stable friction behavior. This indicates that incorporating cBN hard particles effectively enhances the coating's load-bearing capacity while reducing surface plastic deformation and adhesive wear during friction. Three-dimensional topography analysis reveals shallower wear scars and a smoother surface on T2, further validating its superior wear resistance. Wear volume testing also indicates that the wear volume of the T2 coating is significantly lower than that of T1, with a reduction of approximately 80.1%, proving the significant enhancement of the coating's wear resistance due to cBN reinforcement. Analysis of the two-dimensional wear scar curves shows that the T2 coating exhibits smaller wear scar depth and width, with less severe surface damage, further confirming the superior wear resistance of the composite coating.

In summary, the JG-2+cBN composite coating prepared via laser cladding technology demonstrates remarkable effectiveness in enhancing the wear resistance of nickel-based alloy surfaces. It provides an effective solution for further extending the service life of critical nickel-based alloy components. This research offers significant theoretical foundations and experimental references for surface strengthening and remanufacturing of nickel-based alloys, exhibiting substantial potential for engineering applications.

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