

# Research Progress on Laser Cladding Coatings

Ruohui Shuai<sup>1, 2, \*</sup>, Ji Zhou<sup>1, 2</sup>, Jikai Yang<sup>1, 2</sup>

<sup>1</sup> Tianjin University of Technology and Education, National and Local Joint Engineering Laboratory of Intelligent Manufacturing Technology for Automotive Molds, Tianjin 300222, China

<sup>2</sup> Tianjin Key Laboratory of High-Performance Precision Forming Manufacturing Technology and Equipment, Tianjin 300222, China

\* Corresponding Author: Ruohui Shuai

## ABSTRACT

Laser cladding technology, as an efficient surface modification and remanufacturing method, has attracted widespread attention in the fields of material surface strengthening and repair of failed components due to its concentrated heat input, good metallurgical bonding between the cladding layer and the substrate, and strong controllability of microstructure. Research on laser cladding coatings based on different alloy systems has achieved extensive results in process parameter optimization, microstructural evolution, defect control, and performance enhancement. This paper systematically reviews relevant domestic and international studies on laser cladding coatings published over the past decade, with a focus on the microstructural characteristics and performance of nickel-based, cobalt-based, iron-based, and composite coatings. The mechanisms of microstructure formation during laser cladding and their effects on mechanical properties, wear resistance, and corrosion resistance are summarized. On this basis, common issues and development trends in current research are analyzed and discussed, aiming to provide references for further studies and engineering applications of laser cladding coating technology.

## KEYWORDS

Laser Cladding; Surface Strengthening; Microstructure; Properties.

## 1. INTRODUCTION

Laser cladding, as a high-energy-beam surface modification and remanufacturing technology, has attracted widespread attention in the fields of high-end equipment manufacturing and critical component repair due to its concentrated heat input[1], low dilution rate[2], and the ability of the coating to form good metallurgical bonding with the substrate[3]. With the continuously increasing demands on material service performance in industries such as aerospace, energy and power, rail transit, and heavy machinery, single materials can no longer simultaneously meet multiple requirements including wear resistance, corrosion resistance, high-temperature resistance, and fatigue resistance. Enhancing component functionality by preparing high-performance cladding coatings on substrate surfaces has therefore become an important approach for improving the comprehensive performance of components. In practical applications, nickel-based[4], cobalt-based[5], titanium-based[6], high-entropy alloy, and composite coatings have been widely used in high-temperature, heavy-load, and complex media environments. Nevertheless, cladding layers still face many challenges in terms of microstructural uniformity, defect control, and service stability. Different material systems exhibit significantly different responses to laser processing parameters, and the solidification behavior of the molten pool is highly complex. Issues such as cracking, porosity, and elemental segregation have, to a certain extent, restricted the further promotion and application of

laser cladding technology [7]. Therefore, it is necessary to systematically review existing studies to clarify the development trajectory, research focuses, and existing problems of laser cladding coatings, so as to provide a clear cognitive basis for the sustained and in-depth research in this field.

Against this background, the core objective of conducting a literature review on the research status of laser cladding coatings is to elucidate the intrinsic relationships between microstructural evolution and performance variations of cladding layers under different material systems and processing conditions. It aims to summarize the main understandings formed in the academic community regarding process optimization, defect suppression, and performance regulation, while identifying commonalities and divergences among existing research conclusions. Through a systematic analysis of published results, guidance can be provided for subsequent studies in material selection, parameter design, and performance evaluation methods, helping to avoid repetitive exploration and to establish a theoretical foundation for proposing targeted research ideas with clearer technical orientation and academic value.

The literature review in this study mainly covers research published over the past decade, supplemented by a limited number of representative early classical studies to ensure continuity in understanding the technological evolution. The reviewed literature includes Chinese and English journal articles, academic theses, and selected conference papers. The research content focuses on the microstructural characteristics, performance behavior, effects of process parameters, and engineering application performance of laser cladding coatings. The disciplinary scope primarily involves materials science and engineering, surface engineering, and mechanical engineering. The research objects encompass common engineering materials such as steels, non-ferrous metals, and their alloys. Literature sources are mainly drawn from domestic and international academic journals and research outputs from universities, with the aim of constructing a representative research landscape within a limited scope to support the comprehensive evaluation of the research status in subsequent chapters.

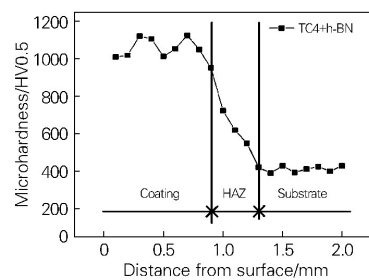
## **2. LASER CLADDING SURFACE STRENGTHENING COATINGS**

### **2.1. Microstructural Characteristics and Performance of Laser Cladding Coatings in Different Material Systems**

Studies on the applicability and microstructural evolution of laser cladding coatings in different material systems have been extensively carried out, covering nickel-based, titanium-based, cobalt-based, high-entropy alloy, and copper-based alloys. Cui Quanwei[8] investigated IN718 nickel-based superalloy and systematically analyzed the combined effects of laser power, scanning speed, powder feeding rate, and substrate temperature on the microstructure and properties of the cladding layer. The results indicated that the precipitation of Laves phases was closely related to Nb element segregation, and the microstructural origin of crack initiation in the middle region of the cladding layer was clarified. From the perspective of non-uniform microstructural distribution, this study explained the tendency of cracks to concentrate in the middle region during multilayer cladding, providing a clear microstructural basis for subsequent crack control. Zhu Ruyi[9] also focused on nickel-based systems and prepared NiCrAlY and self-lubricating composite coatings on an Inconel625 substrate. The introduction of Ag<sub>2</sub>O and Ta<sub>2</sub>O<sub>5</sub> was found to modify dendritic growth behavior and form synergistic lubricating phases in different temperature ranges, thereby significantly improving the friction and wear performance of the coating over a wide temperature range. This study demonstrated that rational design of second-phase constituents can effectively expand coating functionality without markedly sacrificing substrate strength.

In titanium alloy systems, Tan Jinhua et al.[10] prepared metal–ceramic composite coatings dominated by TiB and Ti-B-N eutectic structures by laser cladding TC4+h-BN mixed powders on the surface of TC4 alloy. The coating hardness was significantly enhanced, as shown in Figure 1, and the wear mechanism changed from severe abrasive wear to mild abrasive wear, indicating the

effectiveness of ceramic reinforcement phases in improving the wear resistance of titanium alloys. In earlier work, Molian and Hualun[11] clad BN powders onto Ti-6Al-4V surfaces and confirmed that the formation of hard phases such as TiN and TiB<sub>2</sub> could increase the wear resistance of the coating by more than one order of magnitude. This study verified the feasibility of introducing hard phases into titanium alloy surfaces via laser cladding from the perspective of reaction mechanisms and laid the foundation for subsequent research on titanium-based metal–ceramic coatings. For cobalt-based and composite reinforcement systems, Zou Yun[12] fabricated cobalt-based nanocomposite coatings on INVAR alloy surfaces and found that the synergistic effect of carbide strengthening and interfacial plastic deformation significantly enhanced wear resistance and oxidation resistance, indicating the advantages of multiple strengthening mechanisms in improving the surface performance of special alloys. Similarly, SiC/Co composite coatings prepared by Zhang Weiping et al. [13] exhibited high hardness and excellent friction and wear performance, further confirming the positive role of uniformly dispersed hard phases in enhancing coating properties.



**Figure 1.** Hardness Distribution Map

The introduction of high-entropy alloy systems has provided new ideas for material design in laser cladding. Pang Ming and Ding Qianfeng[14] prepared FeCoNiCrAl high-entropy alloy coatings on the surface of 45 steel and pointed out that microstructural gradient distribution caused by non-uniform undercooling is a key factor affecting interfacial morphology and coating performance. This study emphasized the influence of the complex solidification behavior of high-entropy alloys on the performance regulation of laser-cladded layers.

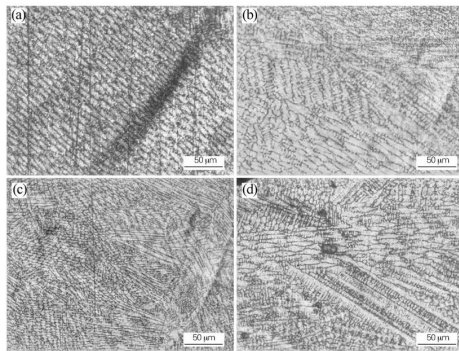
In studies on copper-based alloys, Deng Dewei et al.[15] and Zheng Haitong[16] revealed the morphological evolution of Pb phases and the pore formation mechanisms in Cu-18Pb-2Sn cladding layers from experimental observations and formation mechanisms, respectively. Their results clarified that low-melting-point elements are prone to evaporation and segregation under high-energy beam irradiation, providing important references for the process design of laser cladding in copper-based and other low-melting-point alloy systems. By comparison, although different material systems exhibit significant differences in microstructural evolution paths and performance enhancement mechanisms during laser cladding, they consistently demonstrate the dominant role of process parameters in determining phase composition, grain morphology, and defect formation.

## 2.2. Optimization of Process Parameters and Mechanisms of Defect Formation

Research on cracking, porosity, and residual stress, which are common issues in the laser cladding process, has gradually shifted from empirical parameter adjustment toward quantitative modeling and mechanism-based analysis. Cui Quanwei[8] combined a three-dimensional transient thermal model with orthogonal experiments to establish a quantitative relationship between cladding geometry and process parameters, and further introduced a BP neural network and genetic algorithm to predict and suppress cracking in multilayer cladding. This study demonstrates the potential of data-driven approaches in optimizing complex process parameters. Jun Ma[17], focusing on Fe90 alloy cladding on 42CrMo steel, integrated temperature field and residual stress simulations to develop a residual stress optimization model, achieving a 15.88% reduction in residual stress within the cladding layer. From the perspective of numerical simulation, this work verified the effectiveness of coordinated

parameter optimization in improving the internal stress state of cladding layers. Zeng Jiayi et al.[18] established mathematical models describing the relationships between hardness and pore area of Ni35A+SiC cladding layers using the response surface methodology, and pointed out that laser power and scanning speed exhibit a significant coupling effect on defect control, providing a feasible route for multi-objective process optimization.

With respect to pore defects, Zheng Haitong[16] found through molten pool temperature monitoring that the instantaneous evaporation of Pb and Sn is a major cause of pore formation, and demonstrated that laser remelting can effectively reduce porosity. This work offers a practical process control approach for defect suppression in laser cladding of low-melting-point alloys. Han Jitai et al.[19] inferred microstructural evolution from wear behavior and showed that fine equiaxed grains formed under appropriate laser power conditions contribute to improved coating density and wear resistance. As shown in Figure 2, different laser powers significantly influence the microstructural characteristics of the coating. Overall, studies on process parameter optimization have increasingly integrated experimental methods, numerical simulation, and intelligent algorithms. Nevertheless, significant differences remain in parameter sensitivity and defect response among different material systems, and their common governing mechanisms require further systematic investigation.



**Figure 2.** Microstructure of the 42Cr Mo steel substrate and the clad layer under different laser powers

### 2.3. Performance Regulation Strategies and Engineering Applications

At the level of performance regulation and engineering applications, research emphasis has gradually shifted from basic property characterization to evaluations of service environment adaptability and structural reliability. Du Borui et al.[20] addressed the wear and corrosion issues of hydraulic support columns under complex operating conditions and demonstrated that Fe55 stainless steel cladding layers can significantly enhance wear and corrosion resistance, providing a feasible solution for surface strengthening and remanufacturing of mining equipment. Wu Ying and Liu Lei[21] applied cobalt-based coatings to railway brake discs by laser cladding and, through a combination of bench braking tests and finite element analysis, verified the effectiveness of CoNiTi coatings in suppressing the propagation of thermal fatigue cracks, indicating the engineering application potential of laser cladding under severe thermal shock conditions.

Ojn-Ying Wang et al.[22] and Qin-Ying Wang et al.[23] systematically compared defect evolution and corrosion resistance changes in Ni-Cr-Mo coatings processed by laser cladding combined with remelting treatment. The results showed that remelting can improve microstructural compactness and corrosion resistance without significantly reducing hardness. Da-Wei Zhang et al.[24] and Zhang and Zhang[25] investigated Ni-Cr<sub>3</sub>C<sub>2</sub> and Ni-WC composite coatings from the perspectives of dry sliding wear and erosion-corrosion wear, respectively, revealing the influence mechanisms of carbide dissolution behavior and microstructural morphology differences on wear resistance. From the standpoint of high-temperature service conditions, L. Su[26] pointed out that the wear behavior of laser-cladded alloy layers at elevated temperatures is governed by multiple wear mechanisms acting

simultaneously, highlighting the critical role of temperature in the evolution of coating performance. In earlier application-oriented studies, Sun Fujuan et al.[27] demonstrated through fatigue testing that laser-cladded Al-Y coatings can significantly extend the fatigue life of LY12CZ alloy, reflecting the application value of laser cladding technology in structural repair and life extension. Overall, existing studies have verified the application potential of laser cladding coatings under wear, corrosion, high-temperature, and fatigue service conditions from multiple perspectives, including material design, process optimization, and performance evaluation. Nevertheless, systematic investigations into long-term service stability and multi-field coupled failure behaviors remain insufficient.

### **3. SUMMARY AND OUTLOOK**

From an overall perspective, laser cladding coating technology has achieved relatively systematic progress in the expansion of material systems, understanding of microstructural regulation mechanisms, and pathways for performance enhancement. Existing studies indicate that by rationally selecting cladding materials and appropriately matching laser power, scanning speed, powder feeding methods, and substrate conditions, dense functional coatings with high bonding strength can be fabricated on various engineering materials. In nickel-based, cobalt-based, and their composite systems, researchers have clarified the relationships between dendrite morphology, growth orientation, and cooling conditions, and have realized the coordinated improvement of wear resistance, corrosion resistance, and high-temperature performance through phase composition regulation. Studies on titanium alloys, copper alloys, and steels further demonstrate that laser cladding not only serves as an effective surface strengthening technique but also shows clear advantages in component repair and remanufacturing. In recent years, the introduction of numerical simulation, statistical optimization methods, and intelligent algorithms has promoted a transition in process parameter design from empirical adjustment to model-guided optimization, providing new technical support for improving the stability and consistency of cladding quality. Overall, laser cladding coating research has evolved from single-property enhancement toward multi-property synergistic optimization, with notable improvements in technological maturity and application depth.

Despite continuous accumulation of research Outcome, several issues remain to be addressed. Differences in experimental conditions, evaluation criteria, and testing methods among studies limit the comparability of some conclusions. Although defects such as cracks, pores, and residual stresses in cladding layers have been mitigated to some extent, their formation mechanisms under multi-material and multi-scale conditions are not yet fully unified, and studies on long-term service stability remain relatively limited.

In terms of future development, laser cladding coating research should further deepen the understanding of microstructural and performance evolution under multi-field coupled service environments, while strengthening closed-loop validation between experimental investigations and theoretical models. For engineering applications, greater attention should be paid to the universality and reproducibility of process parameter windows, promoting the translation of laboratory results into large-scale industrial implementation. Methodologically, combining data-driven models with physical mechanism analysis is expected to enhance predictive capabilities for complex solidification behavior and defect evolution. Through sustained collaborative research in material design, process control, and performance evaluation, laser cladding coating technology is anticipated to play a more stable and enduring role in high-end equipment manufacturing and green remanufacturing fields.

### **CONFLICTS OF INTEREST**

The authors declare that they have no conflict of interest.

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