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Research Progress on Ultra-High-Speed Laser Cladding Technology and Its Coating Wear Resistance

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Abstract

Ultra-high-speed laser cladding is an advanced surface coating method, which is widely used due to its characteristics of fast processing speed, small heat-affected zone, dense formed coating, and adaptability to multiple materials. This paper first briefly introduces the characteristics and advantages of ultra-high-speed laser cladding compared to traditional laser cladding technology, analyzes the processing principles of ultra-high-speed laser cladding technology, and combines the latest research to analyze the unique characteristics of ultra-high-speed laser cladding technology. Furthermore, the wear resistance of the coating produced by ultra-high-speed laser cladding technology is analyzed, and finally, based on the current research status at home and abroad, the shortcomings of ultra-high-speed laser cladding technology are discussed, and the development trend of ultra-high-speed laser cladding technology is proposed.

Keywords

Engineering technology; ultra-high-speed laser cladding; coating; wear-resistant and corrosion-resistant; auxiliary laser cladding

Introduction

Coating technology is a widely used surface modification and protection method in which a specific material is applied to the surface of a substrate to enhance its properties. It can improve wear resistance, corrosion resistance, thermal insulation, electrical conductivity, and other characteristics[1]. By enhancing material performance and appearance, coatings add new functionalities, extend service life, and reduce costs. As a result, coating technology has found extensive applications in industries such as manufacturing, automotive, aerospace, electronics, and construction [2][3].

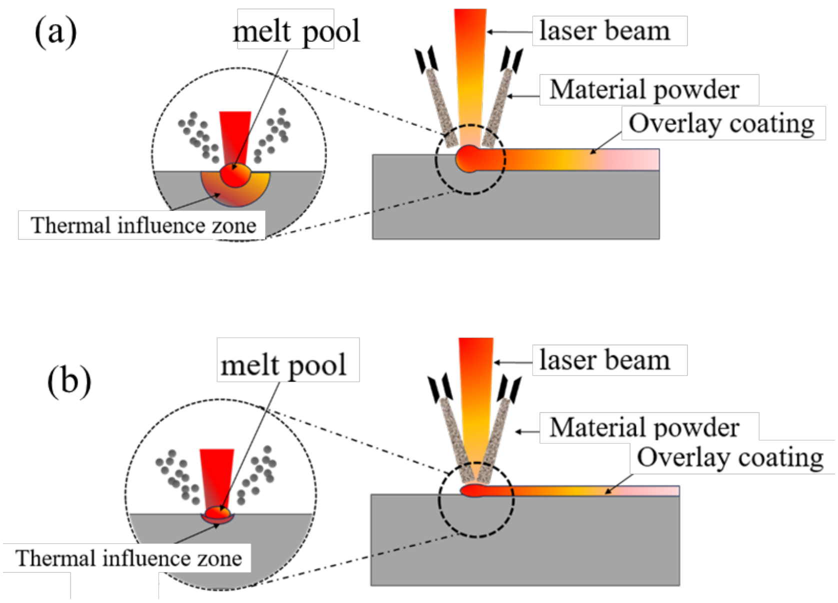
Common coating techniques include thermal spraying[4], chemical vapor deposition (CVD), physical vapor deposition (PVD), electrochemical deposition, and laser cladding. Among these, laser cladding is a surface modification process in which a laser beam melts an additive material (powder or wire) and deposits it onto the substrate surface to form a coating. During the cladding process, the laser beam is focused onto a very small area, instantly melting the additive material and spraying it onto the substrate surface, thereby creating a coating. Such coatings can improve the hardness, wear resistance, and corrosion resistance of the substrate, as well as repair damaged surfaces or impart new functionalities. Because of its advantages—including high precision, a minimal heat-affected zone, wide material compatibility, high efficiency, and reduced material waste—laser cladding is widely employed in surface modification, part repair and remanufacturing, fabrication of complex structures, and material synthesis[5]. However, conventional laser cladding technologies suffer from relatively slow processing speeds and high dilution rates, which limit their suitability for industrial-scale production. In addition, traditional systems have low energy utilization efficiency, with most of the laser energy absorbed by the substrate rather than the additive, thereby restricting their industrial application.

To address these limitations, researchers worldwide have developed a variety of new approaches, including multifunctional laser cladding, fiber-laser cladding, and ultra-high-speed laser cladding. Among them, ultra-high-speed laser cladding offers fast processing, a small heat-affected zone, dense coatings, and strong interfacial bonding. Consequently, it has been widely adopted for producing high-performance surface coatings. In the aerospace sector, ultra-high-speed laser cladding is used to fabricate corrosion-resistant, wear-resistant, and high-temperature oxidation-resistant coatings on superalloy surfaces. In automotive manufacturing, it is applied to repair engine components, enhance wear resistance of automotive parts, and even manufacture precision optical components for engine assemblies[6]. In the electronics industry, this technology enables functional surface modification and repair[7]. This paper analyzes the technical features, processing advantages, current research status, and limitations of ultra-high-speed laser cladding, and offers an outlook on its future development and industrial application.

1. Characteristics and Advantages of Ultra-High-Speed Laser Cladding

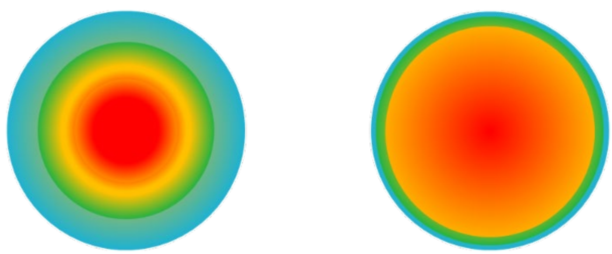
Laser cladding involves locally heating the surface of a workpiece with a high-energy-density laser beam. When the laser energy is absorbed, the surface temperature rises rapidly, causing the targeted metal or alloy material to melt instantaneously and form a molten pool. This molten pool may contain both the unmelted substrate material and the injected feedstock. During laser irradiation, additional material is simultaneously introduced—either by powder injection or powder feeding—into the molten pool, where it interacts and mixes with the molten substrate. Once the laser exposure ceases, the molten pool cools and solidifies quickly, forming a new coating. Because of the rapid heating and cooling involved, the resulting coatings typically exhibit fine grain structures and superior properties.

Ultra-high-speed laser cladding is a high-energy process based on the interaction of a laser beam with the substrate surface, whereby molten metal particles generated under instantaneous high temperatures condense into dense coatings, enabling surface modification, repair, and functionalization. This technique builds on conventional laser cladding by optimizing the interaction position between the powder feed and the laser beam, as illustrated in Figure 1, so that the powder material is already molten when it reaches the substrate surface. In addition, the laser beam profile is changed from a Gaussian to a top-hat (flat-top) distribution, as shown in Figure 2[8], to improve laser energy utilization and the melting rate of the powder material. These improvements significantly increase cladding speed, overcoming the low efficiency of traditional laser cladding while simultaneously enhancing coating quality.



(a) Conventional laser cladding (b) Ultra-high-speed laser cladding

Figure 1. Schematic diagram of the laser cladding process



(a) Gaussian distribution (b) Top-hat beam distribution

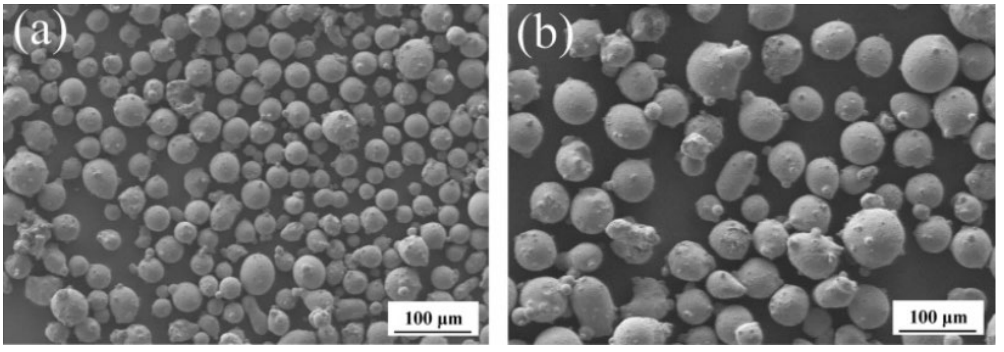
Figure 2. Laser energy distribution

Advantages of Ultra-High-Speed Laser Cladding：

(1) High Processing Efficiency

Ultra-high-speed laser cladding employs higher-power laser sources in combination with advanced control systems, enabling much faster processing speeds and therefore greater productivity compared with conventional laser cladding. In this technique, the laser is focused approximately 0.2 – 3 mm above the substrate surface. By adjusting the powder-feeding nozzle so that the laser beam and powder interact above the substrate, the powder is already in a molten state when it reaches the surface. This greatly improves the deposition efficiency and accelerates the overall cladding process.

Whereas the laser spot diameter in traditional cladding is typically about 3 mm, in ultra-high-speed cladding it is less than 1 mm. This tighter focus concentrates the laser energy, achieving an energy density of up to 3 kW/cm^2. A research team at Xian Jiaotong University reported that cladding speeds as high as 180 m/min can be achieved with this method[9], representing a dramatic increase in processing rate. Because of the higher traverse speeds, ultra-high-speed laser cladding generally uses finer-sized powder particles to ensure efficient melting and deposition.



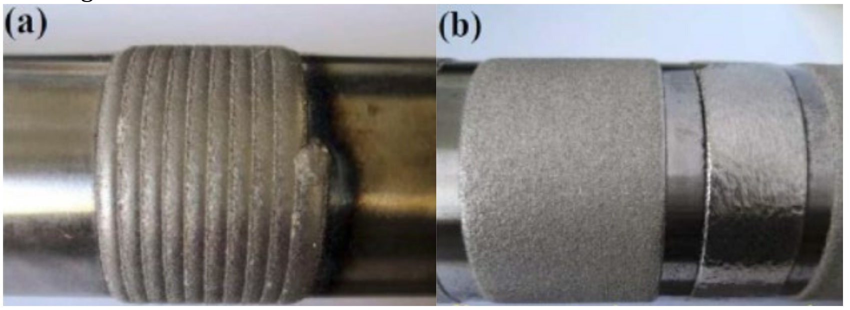
(a) Ultra-high-speed laser cladding (b) Conventional laser cladding

Figure 3. Powder morphology in the two laser cladding processes [24]

(2) High Coating Quality

Conventional laser cladding is often limited by the rates of heating and cooling, whereas ultra-high-speed laser cladding provides superior control over the formation and stability of the molten pool. This enables more precise temperature regulation, which helps to minimize the heat-affected zone and reduce the risk of thermal cracking. Moreover, by optimizing the interaction point between the laser beam and the powder feed, the process redistributes laser energy so that approximately 80 % of the energy is absorbed by the powder and only about 20 % by the substrate. This configuration suppresses the thermal impact on the substrate, lowers the dilution rate, and maximizes the intrinsic properties of the coating material.

Because the powder is exposed to the laser for only a short time and within a limited heating zone, and because the dilution rate is low, the resulting molten pool is relatively small. Consequently, the coatings deposited on the substrate are noticeably thinner than those produced by conventional laser cladding, making the technique particularly suitable for the surface strengthening of precision components. Research teams have already fabricated coatings with thicknesses ranging from 30 μm to 200 μm—comparable to those achieved by electroplating—while the top-hat (flat-top) beam profile produces coatings with higher surface flatness (Figure 4)[10]. In addition, the thinner coatings improve the machinability of the treated surface, alleviating some of the processing challenges posed by the microstructure of thicker claddings.



(a) Conventional laser cladding (b) Ultra-high-speed laser cladding

Figure 4. Surface morphology of coatings produced by different laser cladding processes

(3) Broad Range of Material Applications

Ultra-high-speed laser cladding is suitable for a much wider range of materials and application scenarios than conventional laser cladding. It can successfully process materials that are difficult to handle with traditional methods, such as those with high reflectivity or high thermal conductivity, thereby expanding its industrial applicability.

2. Properties of Coatings Produced by Ultra-High-Speed Laser Cladding

Variations in the process parameters of ultra-high-speed laser cladding result in coating formation mechanisms that differ from those of conventional laser cladding. Extensive experimental studies have been conducted to investigate how this technology influences the macroscopic morphology and microstructure of coatings and to evaluate their performance. These studies have summarized the characteristic features of coating formation and the corresponding process parameters, focusing primarily on coating thickness, surface roughness, dilution rate, microstructural scale, elemental distribution, wear resistance, and corrosion resistance.

2.1. Wear Resistance of Coatings Produced by Ultra-High-Speed Laser Cladding

The rapid heating and cooling inherent to ultra-high-speed laser cladding result in coatings with significantly finer grain structures. Li Baocheng et al.[11] employed this technique to fabricate a Ni625/tungsten carbide (WC) composite coating on 24CrNiMo cast steel. Their study showed that WC particles were uniformly distributed within the coating and that the microhardness increased by approximately 1.25–1.7 times compared with the substrate. This grain refinement markedly enhanced the wear resistance of the coating.

Similarly, Du et al.[12]prepared high-entropy alloy (CoCrFeNiMn) coatings on 316 stainless steel substrates using both conventional and ultra-high-speed laser cladding. Comparative analysis revealed that the coatings produced by the ultra-high-speed process exhibited smaller grain sizes and higher lattice dislocation densities. As the laser scanning speed increased, the dendrite size within the coating gradually decreased, as illustrated in Figure 5. This dendrite refinement increased the surface microhardness and imparted superior wear resistance to the coating.

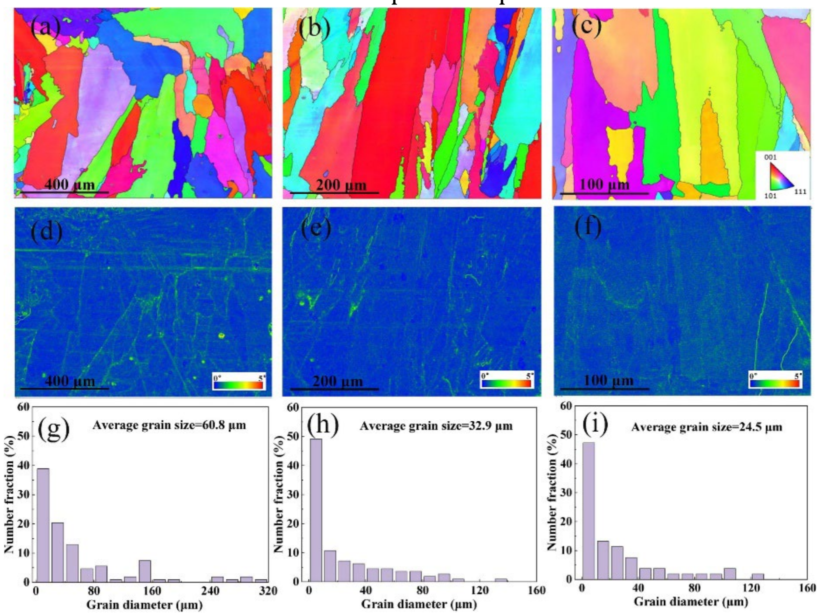


Figure 5. Dendrite size and EBSD maps of coatings at different laser cladding speeds

Li Hui et al. [13]used ultra-high-speed laser cladding to deposit a cobalt-based alloy layer on the surface of 32Cr3Mo1V cast-rolling mill sleeves. Their study showed that the coatings produced by this technique exhibited fine grains, with the dendrites predominantly consisting of densely packed and well-aligned columnar crystals, as illustrated in Figure 6. Measurements further revealed that the microhardness of the coating was significantly higher than that of the substrate, thereby enhancing its wear resistance.

(a) Top region (b) Middle region (c) Bottom region

Figure 6. Microstructures at different locations of the cladding layer

Because ultra-high-speed laser cladding directs considerably less laser energy into the substrate, the resulting coatings exhibit a much lower dilution rate, which in turn helps preserve and enhance the wear-resistant properties of the coating material. Zhang Xin et al.[14] applied ultra-high-speed laser cladding to deposit an Fe–Cr alloy onto a 27SiMn steel substrate. By replacing the conventional circular laser spot with a line-shaped spot and calculating the effect of spot geometry on dilution rate using Equation (1), they found that the resulting coatings had a dilution rate of approximately 10 %, which is far lower than that of conventional laser cladding. This reduced dilution suppressed the substrate's influence on the coating's wear performance.

$$\mu = \frac{\rho_c(x_{c+s} - x_c)}{\rho_s(x_s - x_{c+s}) + \rho_c(x_{c+s} - x_c)}$$

Where ρ_c is the density of the cladding powder, ρ_s is the density of the substrate, x_c is the mass fraction of a specific element in the powder, x_{c+s} is the mass fraction of that element in the resulting coating, and x_s is the mass fraction of that element in the substrate.

Li Chaohui et al.[15] employed high-speed laser cladding to improve the microstructure of SD-Ni45 wear-resistant coatings, reducing the dilution rate and suppressing elemental segregation. Compared with conventional laser cladding, the microhardness of the coatings increased by approximately 30 %. Lou Liyan [16]investigated the effect of ultra-high-speed laser cladding on coating dilution and found that the interface thickness between WC particles and the nickel matrix was about 1 μm. This not only maintained the stability of the WC particles under external forces but also reduced the dilution rate, ultimately producing a nickel-based WC coating with a dilution rate as low as 1 %.

2.2. Corrosion Resistance of Coatings Produced by Ultra-High-Speed Laser Cladding

The extremely high scanning speeds of ultra-high-speed laser cladding induce a greater density of stacking faults and dislocations within the coating, which provides more nucleation sites for the formation of passive films. This promotes the development of dense passive layers on the coating surface, thereby significantly enhancing its corrosion resistance[17]. Shen et al. [18]investigated the corrosion behavior of iron-based alloy coatings and found that, compared with conventional laser cladding, ultra-high-speed laser cladding increased the cladding efficiency by a factor of six and reduced the thermal impact on the substrate. Moreover, coatings with higher chromium content exhibited improved corrosion resistance. The fine dendritic structures achievable with ultra-high-speed laser cladding further enhance the protective properties of the coating.

3. Limitations of Ultra-High-Speed Laser Cladding

The rapid heating and cooling characteristic of ultra-high-speed laser cladding results in minimal molten pool flow, which can generate significant residual stresses, thermal cracks, and porosity during coating formation. These defects can adversely affect coating quality, reducing its strength and durability and making it more susceptible to fatigue and fracture. Furthermore, pores and cracks can act as initiation sites for corrosion, concentrating stress and potentially leading to corrosion fatigue, thereby decreasing the service life of the material. This issue is especially pronounced for high-temperature materials, such as high-melting-point metals and metal-ceramic composites, where local stress concentrations and defects more easily lead to crack formation.

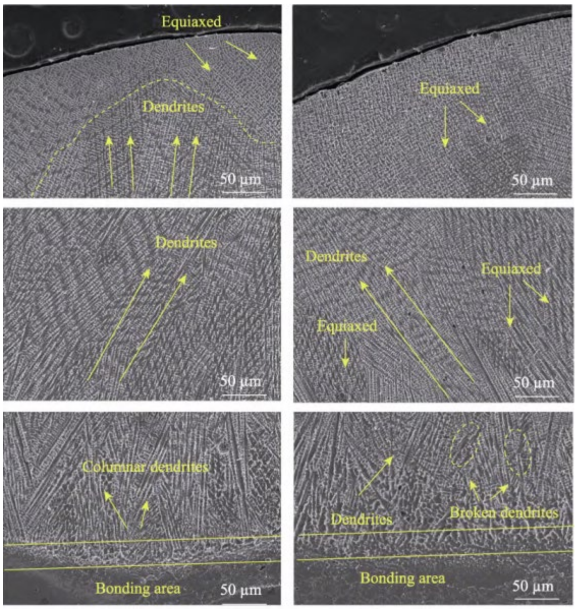
Because the process is extremely fast, there is also a risk that the cladding powder may not fully melt. Therefore, it is necessary to adjust the laser power and the interaction position between the laser beam and powder appropriately based on production requirements to ensure proper melting and coating quality.

4. Assisted Ultra-High-Speed Laser Cladding

To address the limitations of ultra-high-speed laser cladding, researchers worldwide have combined other techniques with the process to improve coating quality and suppress defects such as cracks and porosity.

One approach involves pre-treating the powder or substrate before cladding. Pre-treatment techniques are primarily used to improve the characteristics of the powder and substrate. For example, adding a preheating device within the powder feeder or nozzle can raise the powder temperature, reduce moisture and dust on the powder surface, and enhance powder delivery stability, thereby ensuring the production of high-quality coatings. Similarly, preheating and activating the substrate using auxiliary laser heads or induction heating devices can promote the formation of micro-molten pools, slow the cooling rate, and improve the wettability and diffusion of molten particles on the substrate, enhancing the intrinsic quality of the coating. Laser-based substrate pre-treatment can also modify the substrate surface wettability, which, while lowering dilution rate, improves the overlap and spreading of molten powder on the substrate and accelerates powder flow, ultimately producing coatings with uniform elemental distribution.

During the laser cladding stage, external auxiliary fields can further assist the process. These techniques primarily influence the solidification behavior of the coating and include methods such as magnetic stirring and ultrasonic vibration. Lorentz forces generated by magnetic fields or mechanical forces transmitted via ultrasonic waves can regulate the solidification process, refine grains, improve texture, relieve stress, and reduce coating defects, which is particularly advantageous for fabricating amorphous coatings. Ji Chunyan[19] applied ultrasonic-assisted laser cladding to the surface of IN718 alloy and observed that the ultrasonic field broke up coarse columnar grains, as shown in Figure 7, promoting grain refinement. Li [20]also reported that coatings formed under ultrasonic-assisted cladding exhibited superior wear resistance.

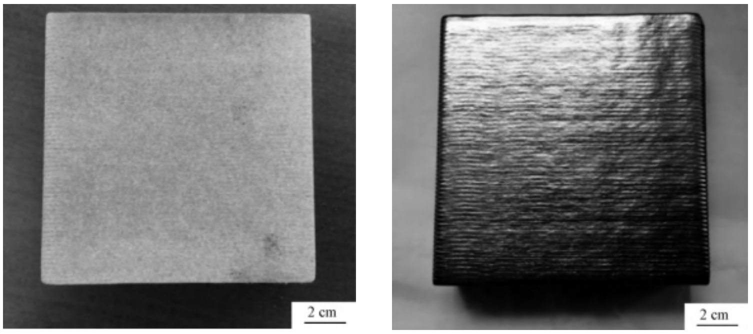


(a) Laser-cladded coating (b) Ultrasonic-assisted laser-cladded coating

Figure 7. Microstructures of coatings produced by different techniques

In summary, various auxiliary techniques can improve coating quality to some extent. However, most external-field assistance methods have been developed for conventional laser cladding. Because ultra-high-speed laser cladding produces smaller molten pools and deposits material at a much faster rate, the effect of auxiliary fields on the molten pool may be limited. Future research should tailor auxiliary techniques to the specific characteristics of ultra-high-speed laser cladding—for example, by applying auxiliary fields at the location where the powder interacts with the laser beam.

Post-processing of the cladded layer can further enhance coating quality. Post-treatment techniques aim to optimize the coating structure and improve performance, such as laser remelting and ultrasonic rolling. Laser remelting involves re-melting and resolidifying the coating, which can further refine grains, reduce defects, decrease surface roughness, and improve surface quality. Liu Mingxia et al. [21] applied laser remelting to a Ni625 alloy coating on a 2Cr13 steel substrate and found that the post-remelting surface exhibited significantly lower roughness, higher density, and no cracks or pores. The surface changes before and after laser remelting are shown in Figure 6.



(a) High-speed laser-cladded coating (b) Laser-remelted coating

Figure 8. Surface morphology of the coating before and after laser remelting

5. Conclusions and Outlook

Ultra-high-speed laser cladding is an efficient and precise surface processing technology with broad application prospects and significant development potential. It is poised to inject new momentum into the advancement of modern manufacturing. Despite considerable progress in studying the wear and corrosion resistance of coatings, many issues remain to be explored, such as the mechanisms by which coating composition, microstructure, and laser parameters affect wear resistance, as well as the design and fabrication of novel wear-resistant coatings. With continued research and development, ultra-high-speed laser cladding is expected to achieve even wider application and greater impact in the future.

By optimizing the interaction position between powder and laser relative to conventional laser cladding, ultra-high-speed laser cladding significantly improves coating quality and processing efficiency. It reduces dilution rates and highlights the wear- and corrosion-resistant properties of the powder, offering new directions for the industrial application of laser cladding.

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