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Research Status of Laser Cladding crack Suppression Technology

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Abstract

As a new type of micro-nano additive technology, laser cladding technology melts powder through a high-power laser beam to form a metallurgically bonded molten pool on the coating surface, which can provide excellent modification functions such as enhancing hardness, wear resistance and corrosion resistance on the workpiece surface. Due to the increase in hardness, the cladding layer is prone to fracture defects. The appearance of cracks seriously affects the service life of the workpiece, poses a great safety hazard to the safe production of enterprises, and greatly limits the application of nickel-based alloy powders. Therefore, this paper summarizes the existing effective technical measures for suppressing crack generation, laying a theoretical foundation for the latter research.

Keywords

Laser cladding; crack; suppression method

Introduction

Laser cladding technology, as an advanced surface modification repair technique, has demonstrated significant application value in harsh environmental fields such as aerospace, petrochemicals, and high-end equipment repair due to its advantages of low dilution rate, dense structure, and good metallurgical bonding. [1] The core principle is to use a high-energy-density laser beam as the heat source, and to form a metallurgically bonded, wear-resistant and corrosion-resistant high-performance cladding layer with the workpiece surface through pre-set powder spreading or synchronous powder feeding at high temperatures. Since the laser cladding technology was proposed in the 1960s, it has evolved from the initial planar single-pass cladding to multi-pass cladding that can adapt to multiple curved surfaces. However, many problems have emerged along with this. Laser cladding, due to its phenomena such as "sudden cooling and heating" [2], mismatch between powder and substrate, and significant differences in thermal expansion coefficients, leads to uneven temperature distribution and excessive stress within the cladding layer, causing damage to the microstructure and ultimately resulting in the generation and propagation of cracks. Therefore, the current research difficulty in laser cladding lies in how to effectively suppress the generation and propagation of cracks. In this regard, this paper briefly introduces the types of cracks and the technical methods for suppressing cracks, and summarizes the methods for controlling cracks from aspects such as process parameters, powder material systems, and external field assistance, providing a theoretical basis and research ideas for the in-depth study of laser cladding cracks [3].

1. Crack generation mechanism

During the laser cladding process, a high-energy laser beam is concentrated within the cladding layer, causing a sharp change in the stress and temperature gradients at that position. When the stress value exceeds the material's strength limit, cracks occur [4]. The causes of cracks can be roughly divided into two types: one is the influence of internal stress, namely thermal stress, organizational stress and constraint stress, caused by the abnormal contraction of various parts due to rapid solidification [5], as shown in Figure 1; The second factor is the influence of cladding materials and processes.

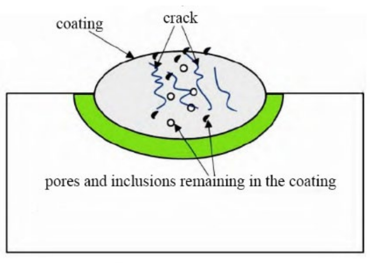

Figure 1. Schematic diagram of cracks in laser cladding coatings [6]

The fundamental cause of cracks in the cladding layer lies in the fact that the stress exceeds its own stress limit, leading to microstructure tearing and thus initiating or expanding cracks. As shown in Figure 2, thermal stress is the internal stress that plays a major role [7]. Due to the significant temperature difference between the cladding layer and room temperature, and the different thermal expansion coefficients of various materials, the cooling contraction rates of the cladding layer vary. The stress formed by the compression of the cladding layer due to the difference in contraction rates is known as thermal stress. The formula is as follows:

$$\sigma = \frac{E\Delta\alpha\Delta T}{1-\gamma}$$

Among them, σ is the thermal stress, E is the elastic modulus of the cladding layer, $\Delta\alpha$ is the difference in the thermal expansion coefficients between the cladding material and the substrate material, ΔT is the difference between the temperature of the laser cladding coating and the room temperature, and γ is the Poisson's ratio of the cladding layer.

It can be seen from the formula that when > 0, the cladding layer is subjected to tensile stress, and the crack sensitivity increases. On the contrary, the crack sensitivity decreases.

Organizational stress is the stress generated by the non-uniformity of the organizational structure transformation between the powder and the substrate in laser cladding throughout the solid-liquid-solid process. The constraint stress is the stress generated when the cladding layer shrinks due to the temperature difference between the cladding layer and the surrounding substrate, squeezing the uncontracted part. The formation of most cracks is related to three types of stress.

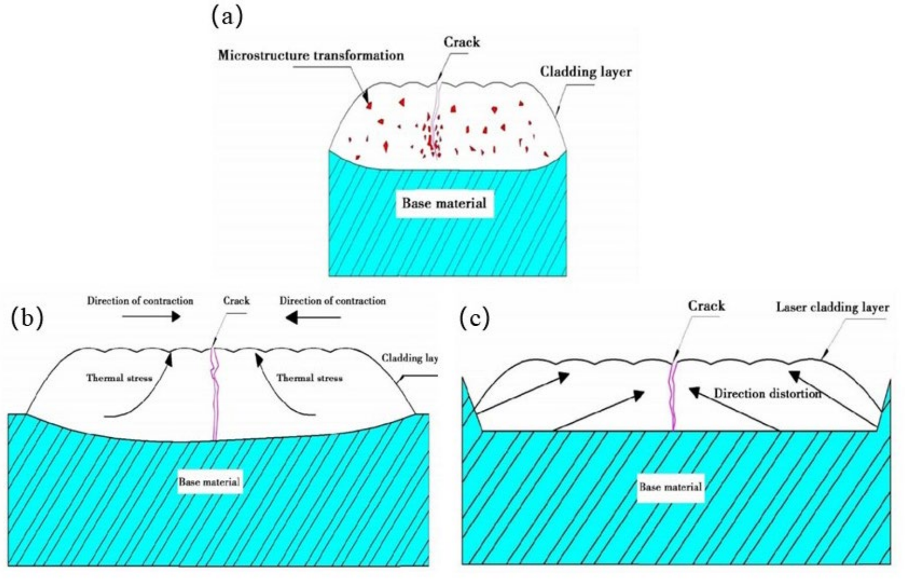

Figure 2. (a) Organizational stress (b) Thermal stress (c) Constraint stress[8]

(2) The existing cladding materials themselves have relatively high brittleness, such as cracks and other defects caused by stress concentration due to element segregation [9]. In iron-based alloys, elemental segregation of B and Si elements is prone to occur, and the atomic diffusion distance is limited, resulting in uneven distribution and the phenomenon of enrichment between dendrites [10], which promotes the formation of cracks. On the other hand, unreasonable setting of process parameters can also promote the formation of cracks. During the cladding process, the number of cladding layers affects the distribution of temperature gradients, and an uneven distribution of temperature gradients is also one of the reasons for the generation of stress. As the number of cladding layers increases, each new layer will impose stress on the original layers. When the stress exceeds that of the material itself, the crack rate will increase significantly, as shown in Figure 3.

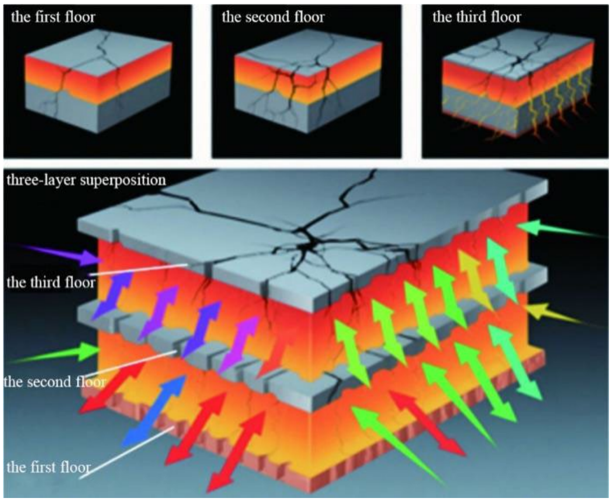

Figure 3. shows the influence of the number of cladding layers on the tendency of crack formation[11]

2. Crack suppression measures

The crack formation factors of laser cladding involve the coupling of multiple physical fields, such as the accumulation and concentration of thermal stress, phase transformation stress caused by microstructure transformation, metallurgical defects resulting from composition segregation, and the mismatch between process parameters and material properties, which together constitute the core inductors of crack initiation and propagation. Based on this, this paper discusses the methods for suppressing cracks proposed by various scholars, which are respectively carried out from three aspects: optimizing process parameters, improving powder systems, physical field assistance, and post-treatment strengthening. The aim is to provide reference techniques for enhancing the excellent stability of coating quality.

2.1. Optimize process parameters

The main process parameters of laser cladding include: laser power P, scanning speed V, spot diameter D, powder feeding rate S, and protective gas flow rate q, etc. The corresponding parameters can be selected according to different laser cladding methods. When pre-setting powder spreading and powder feeding, specific energy is generally introduced for calculation. The main parameters are laser power, spot diameter and scanning speed. These three process parameters jointly define the physical essence of energy density, directly controlling the state of the molten pool and thereby affecting the quality of the cladding layer formation. The following formula is:

$$\rho = \frac{P}{DV}$$

Among them, ρ is the specific energy, D is the spot diameter, P is the laser power, and V is the scanning speed.

Zhang Lei et al. [12] prepared Ni-based alloy cladding layers on the surface of 45 steel at different powers. The study found that the overall crack sensitivity of the cladding layer decreased with the increase of laser power. At lower power, the coating crack sensitivity is relatively high and presents a dense network. As the power gradually increases, the crack density on each cladding channel decreases, dendritic cracks decrease, and dendritic cracks gradually thicken and tend to be parallel. As shown in Figure 4. Ye Junyang et al. [13] prepared Ni60 cladding coatings on the surface of 42CrMo steel. With the increase of laser power, the number of cracks in the cladding layer significantly decreased, but the crack length did not change significantly. Lu Wei [14] found that by controlling the change of laser power with a single variable, the cracking tendency of the coating could be significantly reduced by increasing the laser power and decreasing the powder feeding amount. However, as the scanning speed increased, the crack rate of the coating rose significantly.

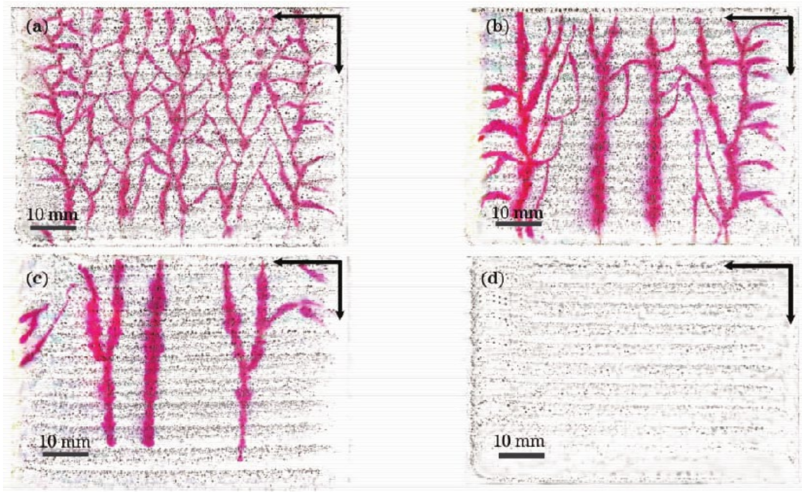

Figure 4. Macroscopic characteristics of surface cracks in laser cladding Ni-based alloy coatings:(a) 2.8Kw (b) 3.2Kw (c) 3.6Kw (d) 4Kw

Specifically, optimizing laser power and scanning speed can be compared with energy balance. The quality of the coating is not the result of individual parameters acting alone, but rather the coordinated matching of P, D, and V, which builds a low-stress and defect-free cladding performance, ultimately achieving a low crack rate of the coating.

2.2. Powder system improvement

Powder optimization design can adjust the component imbalance existing in the powder system. When the thermal expansion coefficients of both are large, it is difficult to completely eliminate cracks merely by adjusting the process parameters. Powder, as the base material of coatings, its composition design and system ratio directly determine the solidification morphology of the structure, which is a key breakthrough in solving crack sensitivity. Yu Ting [15] et al. studied the crack sensitivity of tantalum element to laser cladding Ni60 on medium carbon steel. The results showed that the cracks in nickel-based coatings were mostly characterized by hot cracks. As the Ta mass increases to 10w.t%, both the crack length and quantity decrease, and the wear resistance is also improved. Cui Penghe et al. [16] studied the addition of rare earth Y2O3 to Ni-based powder on the surface of Ti6Al4V. The results showed that the fracture toughness increased by 20% when the rare earth content was 1wt.%, but the fracture toughness decreased as the content further increased. Zhang Leitao et al. [17] found that the optimization and control of process parameters for Ni-based composite coatings with WC content below 30% had a significant effect. The following figure shows the flaw detection images of Ni60/WC coatings with different WC contents at the same power. As can be seen from Figure 5, when the WC content is less than 15wt.%, the coating surface is smooth and free of cracks, and the thermal stress is small. However, when the WC content exceeds 15wt.%, the thermal stress of the coating increases, resulting in larger defects such as pores and cracks on the coating surface. Han Bin et al. [18] investigated Fe901 iron-based powder with CeO2 added on H13 substrate by laser cladding technology. When the CeO2 content was 1wt.%, the number of cracks was significantly reduced, and the crack type transformed into transverse cracks, with a decrease in length.

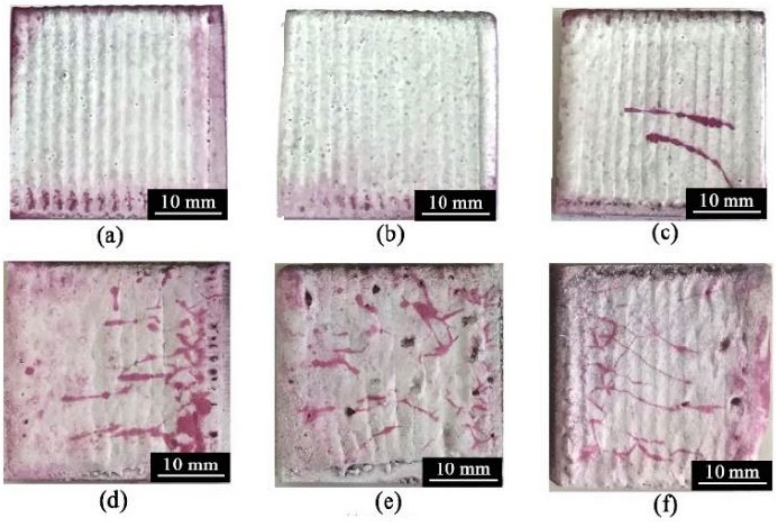

Figure 5. The influence of WC content on surface cracks of coatings[17] :(a) 0wt.%; (b) 15wt.%;(c)30wt.%; (d) 50wt.%; (e) 70wt.%; (f) 90wt.%;

In addition, commonly used additive elements such as Co and Mo can enhance the toughness of the coating and reduce the tendency to crack. Rare earth element oxides are also an indispensable part of suppressing crack formation. For instance, L2O3 can achieve grain refinement under appropriate conditions and react with impurities at high temperatures to realize the function of deoxidation and slag-forming.

2.3. Physical field Assistance

In recent years, to break through the limitations of traditional craftsmanship, various physical fields such as ultrasonic waves, electro-magnetic fields, and vibration fields have been formed. The main approach is to regulate the behavior of the molten pool through an external energy field. Ultrasonic-assisted refinement of dendrite structure through cavitation effect, acoustic flow effect and thermal effect reduces element segregation. Ning et al. [19] prepared Fe-Cr stainless steel parts by ultrasonic vibration-assisted laser cladding and found that the porosity and crack rate of the coating were significantly reduced. Zhuang et al. [20] discovered that ultrasonic vibrations of different amplitudes could all refine the structure and reduce cracks. Electromagnetic field assistance includes steady-state magnetic field regulation and alternating magnetic field regulation. Under the action of Lorentz force, the steady-state magnetic field inhibits the convection of the molten pool, effectively reducing the height of surface ripples. The alternating magnetic field, on the other hand, can enhance the stirring of the molten pool and reduce the number of defects. Qi et al. [21] prepared cobalt-based cladding layers on the surface of 42CrMo through a magnetic field. The magnetoresistive effect reduced the thermal expansion and thermal stress of the coating, thereby lowering the cracking sensitivity of the coating. Lin Yinghua et al. [22] used an electromagnetic composite field to laser-cladding Ni60 coating on AISI 316L stainless steel. After applying the electromagnetic composite field, the longitudinal cracks that occurred without an auxiliary field were suppressed and the crack rate was improved. The vibration field intervenes in the flow rate of the molten pool, inhibits the growth of columnar crystals and releases residual stress by applying periodic vibration effects, thereby improving the quality of the cladding layer. Liu Hongxi et al. [23] applied mechanical vibration to laser cladding Fe-based alloy coatings on 45 steel. When the amplitude was 0.13-0.18mm, the grain refinement effect was the best, and the morphology of the reinforcing phase changed from short rod-like to granular, layered and strip-like. Compared with the cladding layer applied by mechanical vibration, the number of coating cracks under mechanical vibration was reduced. The quality of the coating has been significantly improved. Mechanical vibration can break the growth of dendrite arms in the molten pool through the input of energy during the process, forming equiaxed crystals, which enables uniform grain distribution and enhances the crack resistance. During mechanical vibration, the upward floating and escape of gases and inclusions can also be accelerated. Such pore defects are often stress concentration points that induce cracks, thereby significantly reducing the crack rate of the cladding layer. The following are the common methods of physical field assistance at present.

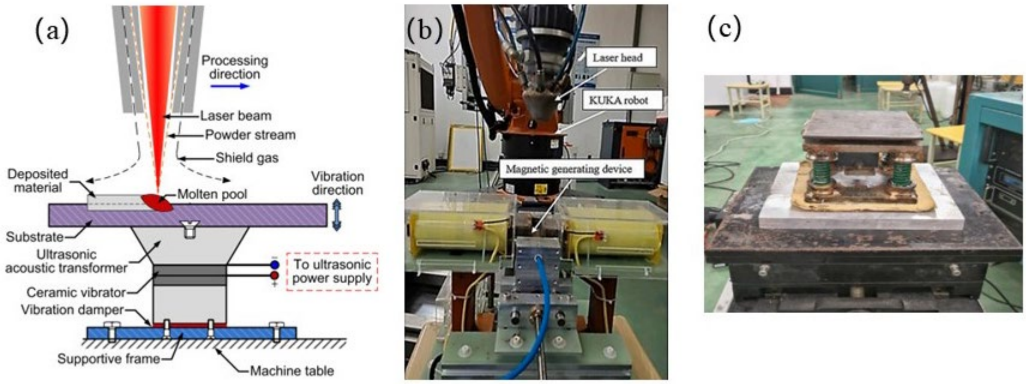

Figure 6. (a) Ultrasonic Vibration[19] (b) Electromagnetic Field Assisted [24] (c) Mechanical Vibration [25]

3. Conclusion and Outlook

Laser cladding technology, as a green remanufacturing technology, is booming. However, with the increase in the hardness of cladding materials, the problem of coating cracks urgently needs to be solved at present. Although many breakthroughs have been made in crack research at present, due to the fact that the generation of cracks involves the coupling effect of numerous factors, it is particularly important to simultaneously achieve the selection of an appropriate cladding material system, the customization of suitable process parameters, and the selection of which physical field to assist in comprehensively eliminating cracks. In subsequent development, simulation analysis can be leaned towards, and a complete simulation model can be established to simulate the laser cladding pool, verifying the optimal promotion effect under multiple physical fields. Enrich AI algorithms to create a complete material-matrix database and achieve crack prediction and detection. With the development of technology, the crack problem will eventually be overcome, and laser cladding will become a key application technology in industrial applications.

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