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International Journal of Mechanical and Electrical Engineering
ISSN: 3005-9615 (Print), ISSN: 3005-7132 (Online) | Volume 3, Number 2, Year 2024
DOI: https://doi.org/10.62051/ijmee.v3n2.06
Journal homepage: https://wepub.org/index.php/IJMEE/index

Research Status of Electromagnetic Field-Assisted Laser Cladding Technology

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ABSTRACT

Laser cladding technology, renowned for its superior surface modification capabilities, is extensively utilized across aerospace, automotive, energy, chemical, metal products, and other heavy industrial sectors. However, issues such as porosity, cracks, and the non-uniformity of the cladding layer's composition and microstructure significantly hinder the advancement of this technology. Therefore, improving and enhancing the quality of the cladding layer is of paramount research importance. In recent years, there has been a growing body of research on the use of external physical fields to assist laser cladding. This research has expanded beyond the application of single physical fields to include the integration of electromagnetic fields, electromagnetic ultrasonic fields, and other coupled physical fields, which have effectively addressed the current challenges faced by laser cladding technology. This paper provides a comprehensive review of the progress made in the field of electromagnetic field-assisted laser cladding, based on an introduction to the principles and mechanisms of electromagnetic field assistance.

KEYWORDS

Laser Cladding; Electromagnetic Fields; Multi-Field Coupling; Research Status.

1. INTRODUCTION

Laser cladding is a surface treatment technology that utilizes a high-energy-density laser beam to rapidly heat and melt the added material, forming a uniform metal layer on the substrate surface[1,2]. Compared to traditional surface modification processes such as overlay welding, thermal spraying, and plasma spraying, laser cladding offers advantages such as rapid solidification, low heat input, minimal thermal deformation, and low dilution rate. Consequently, it is widely used in the surface repair and enhancement of critical components in automotive manufacturing and petrochemical industries. Despite the rapid advancements and widespread applications of laser cladding technology in recent years, several issues persist that constrain its development, including metallurgical quality of the cladding layer, porosity, cracks, and non-uniformity in composition and microstructure, which represent significant bottlenecks.

Applying external electromagnetic fields to regulate the solidification microstructure is a promising approach to improve coating quality. This method can optimize the performance and quality of the cladding layer, rather than solely relying on material design and process parameter control to eliminate defects[3-5]. Electromagnetic fields influence the heat and mass transfer in the molten pool without coming into contact with the material, thus avoiding contamination of the cladding layer. Additionally, the magnetic field promotes the flow of the molten material within the pool, disrupting

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and breaking up large dendrites to form finer equiaxed grains, thereby enhancing the mechanical properties of the cladding layer.

2. ELECTROMAGNETIC FIELD ASSISTED LASER CLADDING MECHANISM

2.1. Electromagnetic Stirring Effect

After the incorporation of electromagnetic field assistance, the laser cladding pool is influenced by both natural convection and electromagnetic forces. This effect is primarily achieved through the electromagnetic force generated by applying alternating current, which enhances the convection, heat transfer, and mass transfer within the pool. Additionally, the shear forces generated by different flow velocities contribute to breaking up dendrites, leading to a more uniform microstructural distribution [6].

2.2. Joule Heating Effect

The Joule heating effect, also known as the resistive heating effect, refers to the heat generated due to the resistance of a conductor when an electric current passes through it. This phenomenon was discovered by the physicist James Joule. The fundamental principle of the Joule heating effect can be expressed by the following formula:

$$Q = I^2 Rt \tag{1}$$

In the formula, Q is the heat generated, I is the electric current, R is the resistance of the conductor, and t is the time during which the current passes through the conductor.

Due to the temperature and heat generated by the Joule heating effect, the temperature gradient distribution within the molten pool is affected, leading to a reduction in the overall cooling rate of the molten pool. This, in turn, diminishes the undercooling during the solidification process[7].

2.3. The Skin Effect

The skin effect refers to the phenomenon where, in an alternating current passing through a conductor, the current density is higher at the surface of the conductor and gradually decreases towards the interior. As a result, the internal current of the conductor is relatively small, and the current predominantly flows through a thin layer near the surface of the conductor. The depth of penetration is given by:

$$\chi = \frac{1}{\sqrt{\pi\sigma\mu f}} \tag{2}$$

where:δ is the skin depth;σ is the electrical conductivity of the material;μ is the magnetic permeability of the material;f is the frequency of the current being conducted.

According to Faraday's law of electromagnetic induction, a varying magnetic field induces an electromotive force (EMF) within the conductor. This induced EMF opposes a portion of the current, resulting in a reduction in current density within the conductor[8].

2.4. Electromagnetic Braking Effect

Under the influence of an external magnetic field, the molten metal cuts through the magnetic flux lines, generating induced currents. According to Fleming's left-hand rule, the direction of the induced currents is opposite to the direction of the molten pool flow. Consequently, this effect suppresses convection within the molten pool[9].

2.5. Theemoelectromagnetic Fluid Effect

During the laser cladding process, the initially precipitated solid phase can coexist with the molten phase. There is a significant temperature difference between the solid and liquid phases. Since both the molten metal and the solid phase are conductors, the different thermoelectric potentials of the solid and liquid phases generate thermoelectric currents. The interaction between these thermoelectric currents and the applied electromagnetic field produces thermoelectromagnetic forces, which drive the movement of the molten phase[10].

3. EFFECT OF DIFFERENT ELECTROMAGNETIC FIELD-ASSISTED LASER CLADDING ON COATING PROPERTIES

3.1. Single Field Assisted Laser Cladding

The application of external magnetic fields during the metal solidification process can be traced back to the mid-20th century. Langenberg et al. observed that applying an alternating magnetic field during steel ingot solidification resulted in finer grain structures. Since then, research into magnetic field control of the metal solidification process to improve microstructural properties has grown significantly. Today, the use of external magnetic fields in metal solidification is widespread in fields such as casting and welding. The primary types of external magnetic fields include steady magnetic fields, alternating magnetic fields, and pulsed magnetic fields.

3.1.1. Magnetic Field.

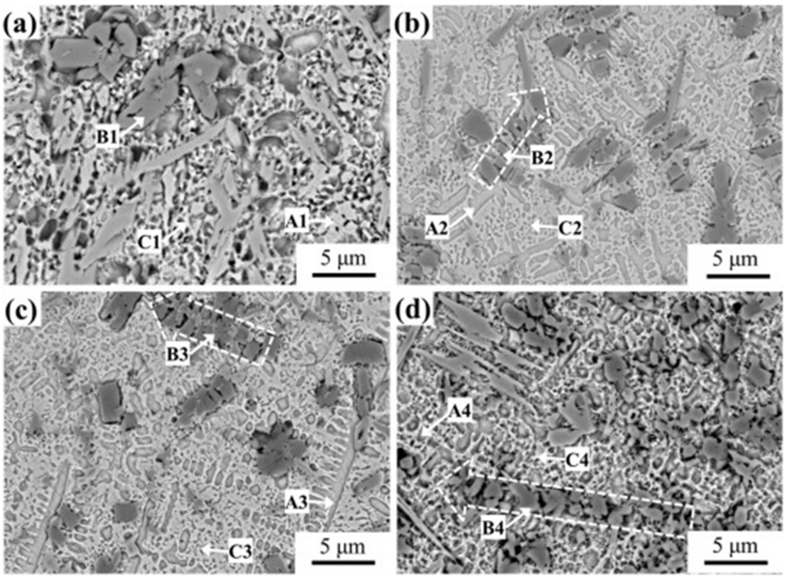

Fig 1. SEM morphology of the central region of coatings prepared under different steady-state magnetic field induction intensities:(a)0T(b)0.1T(c)0.15T(d)0.2T

Steady magnetic fields are a type of magnetic field generated by permanent magnets or electromagnets with direct current, where the magnetic field strength and direction remain constant over time. Qian Wang et al. [11] employed steady-state magnetic field-assisted laser cladding technology to fabricate nickel-based coatings on a pure iron substrate. They investigated the effects of steady-state magnetic fields on nickel-based coatings by analyzing the coating's macroscopic morphology, phase composition, microstructure, and elemental composition. The results indicate that the external steady magnetic field can suppress surface waviness in the coating without affecting its phase composition. As shown in Fig.1, with increasing magnetic field strength, the grain size decreases, and the length of the hard phases' structure significantly increases under the influence of the magnetic field, with growth directions almost parallel to the magnetic field direction. The surface morphology of the coating is primarily influenced by the electromagnetic braking effect, while the solidification microstructure is mainly affected by the thermoelectromagnetic fluid effects.

3.1.2. Non-steady Magnetic Field.

The flow of liquid metal in an alternating magnetic field induces eddy currents, which interact with the magnetic field to generate electromagnetic forces that drive the movement of the melt. This phenomenon intensifies convection in the liquid metal and facilitates heat and mass transfer within the melt pool. Electromagnetic stirring technology enhances convection by applying an alternating/rotating magnetic field during the solidification process, thereby improving the quality of the coating.

Jiang P et al.[12] employed rotating magnetic field-assisted laser cladding to create nickel-based coatings on a Q235 substrate, as illustrated in Fig.2. Analysis of the experimental results revealed that during the solidification process, the Lorentz force generated by the rotating magnetic field stirs the melt pool, promoting a uniform distribution of phases within the coating and reducing solidification stresses caused by differential solidification shrinkage between phases. Consequently, the number of cracks within the coating was significantly diminished; the average grain size decreased from 0.67 μm² to 0.49 μm², while the average microhardness increased by 18%, and the wear rate decreased by 83.7%, indicating a substantial enhancement in overall performance.

As shown in Fig.3(a1) and 3(a2), in the absence of the rotating magnetic field, Marangoni convection is present in the melt pool, with dendrites influenced solely by buoyancy (Fb), gravity (G), and surface tension (Fs). Following the introduction of the rotating magnetic field, as depicted in Fig.3(b1) and 3(b2), Marangoni convection persists, while the Lorentz force (Fl) generated by the rotating magnetic field acts at points a and b.

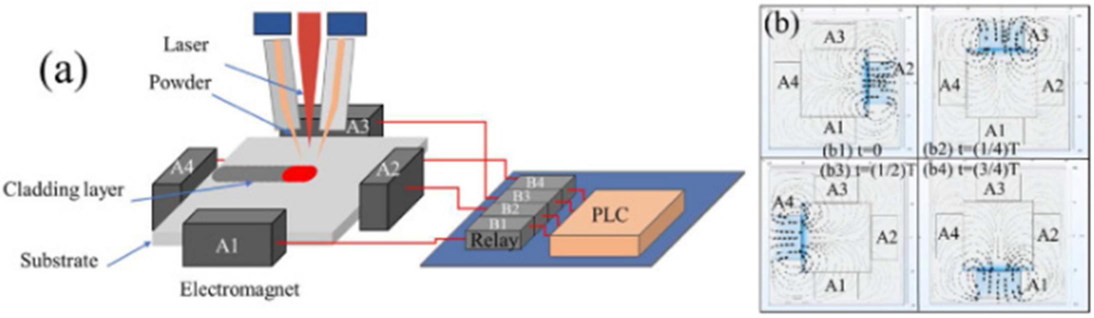

Fig 2. Rotating Magnetic Field-Assisted Laser Cladding

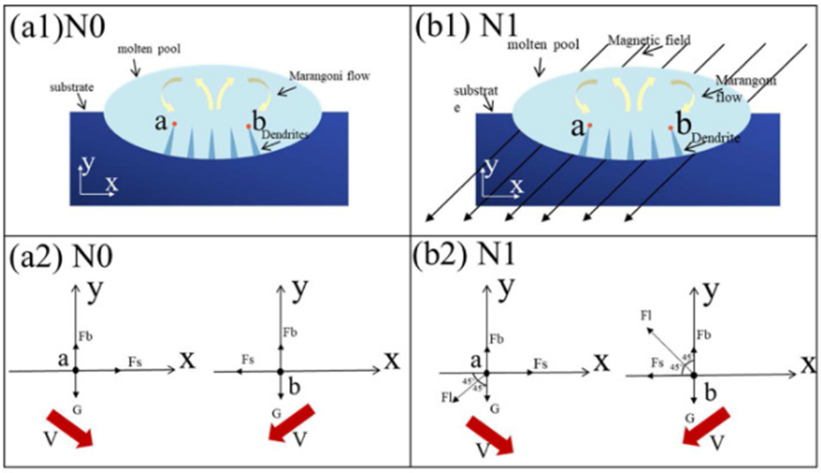

Fig 3. Stress Analysis of the Melt Pool

Unlike steady magnetic fields and alternating/rotating magnetic fields, pulsed magnetic fields can be understood as controlling the strength, direction, frequency, and other parameters of the magnetic field to exert intermittent effects on the molten metal. The magnitude and intensity of the pulsed magnetic field vary periodically with the discharge voltage, resulting in the generation of Lorentz forces in the molten metal that change over time. This variation induces oscillations and stirring effects within the melt pool. The pulsed magnetic field exerts radial and axial forces on dendrites, leading to the fragmentation of growing dendrites, inhibiting their growth, and refining the microstructure of the solidified metal. Currently, research on pulsed magnetic field-assisted laser cladding remains limited due to the short existence time of the melt pool during the laser cladding process. Chen Z et al. [13] utilized magnetic field-assisted laser cladding to fabricate Ni60 coatings on a 45 steel substrate, investigating the effects of no auxiliary field, steady magnetic field, alternating magnetic field, and pulsed magnetic field on the coating's performance. The results indicated that the application of a magnetic field significantly reduced the number of cracks, promoted grain refinement, and increased coating hardness, with the alternating magnetic field demonstrating the most pronounced effect on grain refinement and hardness improvement. However, the pulsed magnetic field resulted in severe segregation of hard phases.

3.2. Single Electric Field-Assisted Laser Cladding

The application of a single electric field is relatively common in metal forming fields, particularly in welding and casting, but is less explored in laser cladding. The types of electric currents used include direct current (DC), alternating current (AC), and pulsed current, each producing distinct physical effects and playing different roles. DC and AC are continuous currents; when applied during the metal solidification process, they induce directional movement of different ions within the melt. Additionally, the Joule heating caused by the current leads to temperature changes in the melt, thereby affecting its undercooling and influencing the metal solidification process. Lulu Zhai et al. [14] investigated the impact of AC on the morphology, microstructure, and properties of laser-cladded Ni-Cr-B-Si coatings. The study demonstrated that under the influence of the AC field, the nucleation rate was enhanced, grain size was refined, and the coating exhibited a significant reduction in cracks, increased average hardness, and improved corrosion resistance. Xie Deqiao et al. [15] employed pulsed current-assisted laser cladding to produce FGH95 alloy coatings. Analysis of the experimental results revealed that the electromagnetic forces generated by the pulsed current compressed the melt pool, reducing porosity. Pulsed current also increased the undercooling for crystal nucleation, refined the grain size, and decreased the size of MC carbides, thereby enhancing the high-temperature performance of the nickel-based alloy.

3.3. Electromagnetic Composite Field-Assisted Laser Cladding

Current research on single physical field-assisted laser cladding is becoming increasingly mature. However, the limitations of using a single physical field are still present and may no longer meet processing requirements. To better leverage the benefits of physical field-assisted laser cladding, multi-physical field coupled laser cladding is now under investigation. Multi-physical field composite processing aims to achieve effective control over the solidification process of the melt pool through its complex coupling processes, which produce results exceeding those of simple physical field superposition. Electromagnetic field coupling primarily utilizes electromagnetic forces generated by electromagnetic reactions to influence the flow state of liquid metal, thereby improving the microstructure of the solidified metal [16,17]. Depending on specific needs, the electromagnetic field coupling can be designed as a steady magnetic field combined with an AC electric field or an alternating magnetic field combined with a DC electric field. Each design is tailored to different characteristics, but the underlying principle remains similar: when current flows through the melt, it generates electromagnetic forces, specifically Lorentz forces, within the magnetic field, affecting the convection of the melt and, consequently, its microstructure. The direction and nature of these electromagnetic forces are determined by the magnetic field and current direction. Varying electromagnetic forces can induce oscillations in the melt pool, refine the grain size, while stable electromagnetic forces regulate and enhance the direction of melt movement, improving processing stability.

Research on the application of electric and magnetic field coupling for regulating metal solidification has also been among the earliest applications in casting and related fields. Lei Hang et al.[18] conducted a study where an alternating electromagnetic field was applied to assist laser cladding of Fe901 powder on Cr12MoV steel during the laser cladding process, the electromagnetic assistance device is illustrated in Fig.4.. The results indicated that the stirring effect generated by the electromagnetic field caused convection within the melt pool, increasing surface waviness but also leading to dendrite breakage and grain refinement. This stirring effect led to a more uniform temperature distribution in the melt pool. As the number of cladding layers increased, the microstructure of the coating formed under the influence of the electromagnetic field gradually transformed from columnar dendrites to equiaxed grains. Long Chen et al. [19] designed a DC electric field coupled with an alternating magnetic field device to assist in the laser cladding of 304 stainless steel alloy coatings. They investigated the effects of the electric and magnetic fields on the macro morphology and mechanical properties of the cladding layers and utilized finite element simulation to analyze the melt pool flow under the influence of these fields. The study demonstrated that applying the electromagnetic composite field increased the grain refinement zone of the cladding layer, promoted element exchange between the substrate and the cladding layer, and improved the coating's microhardness and wear resistance. Finite element simulations of the melt pool flow under the influence of electric and magnetic fields revealed that the application of the electromagnetic field accelerated melt pool flow, generated multiple vortices, and enhanced the stirring effect on the melt pool.

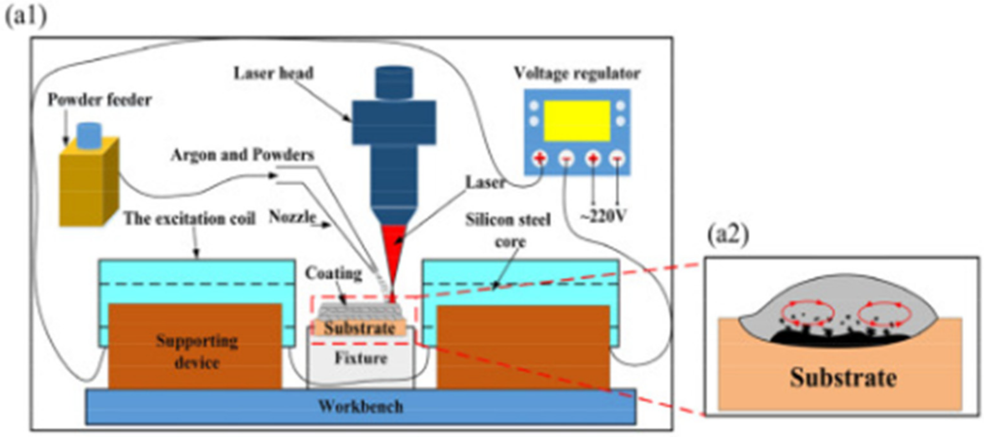

Fig 4. Schematic Diagram of Electromagnetic Field-Assisted Laser Cladding Process

4. SUMMARY

4.1. Summary

The above analysis indicates that electromagnetic field-assisted cladding technology significantly improves coating quality by enabling control over microstructure, refining grain size, and suppressing compositional segregation. However, current research depth is insufficient for the widespread application of electromagnetic field-assisted laser cladding technology. Therefore, future research should focus on the following areas:

1. Establish experimental correlations between laser power, scanning speed, and electromagnetic field parameters, selecting appropriate laser parameters based on different electromagnetic field strengths.

2. Current research on electromagnetic field-assisted laser cladding primarily focuses on performance testing, with electromagnetic field generation devices and lasers operating separately. This limitation hinders cladding on complex surfaces. Thus, it is necessary to develop equipment that integrates and synchronously operates electromagnetic field assistance devices and lasers.

4.2. Hasdfhask

CONFLICTS OF INTEREST

The authors declare that they have no conflict of interest.

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