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Research and development status of laser cladding on magnesium alloys: A review

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ABSTRACT

Magnesium alloys are one of the most promising lightweight structural materials. However, the poor corrosion and wear resistance restrain their further application. As a kind of surface modification technique, laser cladding treatment is superior to others owing to its unique characteristics such as high efficiency and the metallurgical bonding between the coatings and substrates. In this paper, the laser cladding process and the effects of processing parameters, including laser power, scanning velocity, beam focal position, feeding ways of the material etc., are discussed in detail. The material systems preplaced on magnesium alloys are summarized. Except for the traditional metallic materials, novel ternary alloys, amorphous alloys and high entropy alloys (HEAs) are widely used and apparent advantages are exhibited. In terms of the problems existing in the laser cladding process of magnesium alloys, some potential solutions and the development tendency are reviewed.

1. Introduction

Magnesium alloys have developed into one of the most promising candidates as structural materials [1–3]. They have good castability, machinability, high strength-to-weight ratio, and some advantages in price due to the abundant reserves on the earth and in the sea [4]. Magnesium alloys, whose densities are approximately 35% smaller than that of aluminum alloys and 65% smaller than that of titanium alloys [5], have been widely used in the fields of automotive and aerospace. Magnesium alloys are increasingly used in fabricating certain parts in automotive field, such as engine block, steering wheel frame, seat frame, and so on [6]. Exceptionally, the excellent electromagnetic shielding and damping capacities make them better properties of protecting signal and reducing the noise, and gradually replace the plastic in electronic industries [7]. However, poor galvanic corrosion characteristic [8] shortens the service lives of magnesium alloys parts under certain application circumstances, especially in wet and salt-laden environments. Similarly, the poor wear resistance [9] and high-temperature stability [10] inhibit their further applications in industries.

Nowadays, relevant researches are needed on magnesium processing, alloying and surface treatment techniques [6]. Various surface modification techniques have been adopted to enhance the mechanical properties of magnesium alloys, such as chemical conversion [11], physical vapor deposition (PVD) [12,13], chemical vapor deposition (CVD) [14], micro-arc oxidation (MAO) [15,16] or plasma electrolytic oxidation (PEO) [17], diffusion treatment [18], electroless plating [19], and so on. Jiang et al. [11] fabricated Ce-V conversion coating on AZ31 magnesium alloy. The coating contained amorphous microstructure, and showed better corrosion resistance than the as-received substrate. However, cracks formed on the surface and a double-layer structure was observed owing to the different elementary composition, which was detrimental to the properties of the coating. Mao et al. [12] reported certain behaviors of the carbon film with electroless nickel interlayer (Ni+C) on GW83 (Mg-8Gd-3Y-0.5Zr) magnesium alloy deposited by PVD. Though the method solved the common problem like low adhesion force between the coating and substrate in some extent, the thin and porous carbon film was prone to form galvanic cells and it was disadvantageous to enhance the property of corrosion resistance.

In recent decades, laser has been widely used in material cutting and manufacturing processes owing to its high energy density [20–23], and the laser surface treatment has been a research hotspot. Laser surface treatments, including laser alloying [24], laser remelting [25], laser cladding [26], laser shot peening [27], and so on, have gone through rapid developments owing to their many particular advantages. The

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treatments would develop coatings on the surface without damaging the shape and inherent properties of the bulk materials, but having the effects of surface modification or strengthening, sometimes realizing surface repairing [28]. Especially, laser cladding has some brilliant advantages. Firstly, the coatings show strong metallurgical bonding with substrate with a shallow heat affected zone. Secondly, the rapid heating and cooling rates ensure a fine and uniform microstructure. Thirdly, the formation of lots of in-situ intermediate phases and the reservation of the un-molten strengthening phases are favorable for a higher corrosion and/or wear resistance [29,30], better thermal fatigue resistance [31], and useful magnetism properties [32]. More importantly, laser assisted surface modifications have the advantages of environmental friendly, simple, flexible, time-saving and material-saving [25]. Rolink et al. [33] compared the thermal resistance of the samples treated by thermal spraying with that by laser remelting and laser cladding. Results revealed that the laser cladding sample had the highest thermal shock resistance owing to the strong bonding between the coating and substrate.

At present, laser cladding of magnesium alloys has developed into a novel research area. This paper reviews the relevant studies in laser cladding of magnesium alloys from processing parameters optimization and cladding materials selection, summarizes the development status, puts forward the current problems and makes prospect to the future development tendency. This paper is expected to play a guiding role for the studies in this area.

2. Laser cladding process

Laser cladding is an interdisciplinary technique, which combines the laser technology, computer aided manufacturing (CAM) and the control system together [34]. Laser cladding utilizes a laser heat source to deposit a thin layer of preplaced materials on a moving substrate, as shown in Fig. 1 [35]. Moving of the substrate can be controlled through the operating system. The specimen after laser cladding is usually divided into four parts: cladding zone (CZ), interfacial zone (IZ), heated affected zone (HAZ), and the substrate (SUB) [36].

As mentioned in the *Introduction* section, good metallurgical bonding between the coating and substrate can be obtained with laser cladding technique. In order to promote the further application, more studies should be carried out in the laser cladding process on magnesium alloys. Macro morphologies, microstructures, and properties of the cladding coatings are tested and the results of them are taken as the criteria of the cladding process. And the main influencing factors on the qualities of the coating are summarized, including processing parameters, feeding ways of the material, the cladding material systems.

2.1. The processing parameters

The parameters, such as laser power, scanning velocity, beam diameter, beam focal position, are related to the cladding geometry,

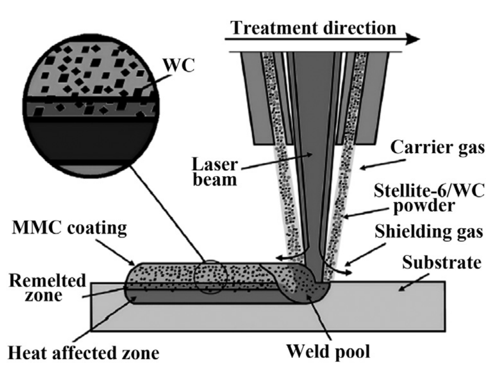

Fig. 1. The schematic diagram of laser cladding process [35].

Table 1
The phases and microstructures under different laser powers [37].

Powers (kW)	2.5	3.0	3.5	4.0
Phases	Mg_2Al_3 (fcc) + P3	P3	P3	α-Mg + P3
Structures	the petal-like phase + S3	S3	S3	the grey zone, the black massive precipitated phase

Note: P3 referred to $Mg_{17}Al_{12}$, Mg_2Si and Mg_2Al_3 (hcp) phase constitution obtained under 3.0 kW; S3 referred to the refined dendrite, needle-like and the grey zone microstructure obtained under 3.0 kW.

dilution rate, layer thickness, aspect ratio, microstructure and the mechanical properties. For example, the low melting points (~560 °C) of magnesium alloys make them liable to be melted during the laser cladding process, and then the coatings are diluted by substrates. The dilution rate values are always changing with the processing parameters [37]. To control the interactions in the molten pool and synthesize coatings which have uniform composition, dense microstructure and better properties, it is essential to adjust the processing parameters.

Gao et al. [37] revealed the influence of laser power on AZ91HP magnesium alloy during laser cladding process. The laser powers were 2.5–4.0 kW with a constant scanning velocity of 300 mm min^{-1} and a laser beam size of 10×1 mm^2. The phase constitutions and microstructures were listed in Table 1. Results illustrated that 3 kW was optimum for the wear resistance. Nevertheless, under the effect of 2.5 kW power, the precipitation of petal-like Mg_2Al_3 phase contributed to the best improvements on corrosion resistance owing to the similar electrode potential with $Mg_{17}Al_{12}$. Under higher powers, the α-Mg solid solution appeared due to the high dilution rate of magnesium, which was detrimental to the corrosion resistance of the coating.

The laser power represents the available energy that can be absorbed by the molten pool. Expect for the influence on phase composition, it affects the surface morphology meanwhile. For example, a very high power might lead to surface evaporation and crater formation. Conversely, a low power would cause inadequate melting and intermixing, leading to inhomogeneous distribution of hard particles [38].

Wang and Yue [39] studied the microstructure and corrosion resistance of the Al-Si cladding coatings fabricated with different laser scanning velocities on ZK60/SiC particle reinforced composite. The cladding coating was divided into the undiluted layer, the diffusive layer, and the interfacial layer under 8 mm s^{-1} scanning velocity. While, only diffusive layer + interfacial layer, and undiluted layer + interfacial layer appeared under the scanning velocities of 5 mm s^{-1} and 10 mm s^{-1}, respectively. Because the Al/Mg_2Si composite in the diffusive layer caused the galvanic corrosion, the corrosion resistance of the coating was not improved greatly. However, the coating treated under 10 mm s^{-1} had a structure of Al-Si eutectic and exhibited the best corrosion resistance due to the absence of Mg_2Si. The laser scanning velocity was found significantly influencing the existing time of the molten pool, the process of heat and mass transferring, the cooling rate, and as a result, the microstructure and composition of the coatings changed with different scanning velocities.

The laser beam focal position was found having non-ignorable influence on the cladding coating. Riquelme [40] researched the effect of three kinds of focus modes (negative defocus, focus, and positive defocus) in Al-SiC_p laser cladding on ZE41 magnesium alloy, as shown in Fig. 2. The optimum focus height was the second focus condition because the preplaced powders were melted by the laser beam and were not rebound away from the surface, so the interface of the coating-substrate was the best (Fig. 2(b)). Under the negative defocus condition, the powders were not completely melted and they tended to be rebound away from the surface without depositing because they never passed through the highest power zone of the beam (Fig. 2(a)). Under the