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Review

Laser surface alloying on aluminum and its alloys: A review

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ABSTRACT

Aluminum and its alloys have been widely used in aerospace, automotive and transportation industries owing to their excellent properties such as high specific strength, good ductility and light weight. Surface modification is of crucial importance to the surface properties of aluminum and its alloys since high coefficient of friction, wear characteristics and low hardness have limited their long term performance. Laser surface alloying is one of the most effective methods of producing proper microstructure by means of non-equilibrium solidification which results from rapid heating and cooling. In this paper, the influence of different processing parameters, such as laser power and scanning velocity is discussed. The developments of various material systems including ceramics, metals or alloys, and metal matrix composites (MMCs) are reviewed. The microstructure, hardness, wear properties and other behaviors of laser treated layer are analyzed. Besides, the existing problems during laser surface treatment and the corresponding solutions are elucidated and the future developments are predicted.

1. Introduction

Aluminum and its alloys have a wide range of applications in aerospace, automotive and transportation industries owing to their excellent properties such as high specific strength, good ductility, high thermal conductivity etc. [1] However, the low hardness and poor wear characteristics limit their wide use especially for the situations where a hard surface is needed [2]. To improve the surface properties, various surface modification technologies have been proposed and investigated [3,4]. Thin strengthened layers can be obtained by various general surface processing including metal matrix composite [5], plasma spraying [6], thermal spraying [7], electroplated coating [8] and hard anodizing [9]. However, these techniques are less frequently employed due to poor metallurgical bonding between the coating and the substrates [10,11]. Moreover, anodizing cannot form a continuous oxide film to protect the surface effectively. Chromate is harmful to the environment and human bodies because of its high toxicity [12].

Comparatively, laser beams are widely used in many fields to improve surface properties of various materials, such as titanium [13], steel [14,15], copper [16] and magnesium [17], thanks to their high coherence, well directionality and high energy density [18,19]. Another advantage of laser surface treatment comes from the fact that laser beam has an excellent spatial resolution which makes it ideal for depositing coating on miniature size components [20]. Laser surface modification techniques include laser surface remelting [21,22], laser surface cladding [23,24], and laser surface alloying [25–27]. By means of high laser power, very high temperature can be reached to melt both the substrate and the strengthened phase, which is beneficial to strong metallurgical bonding [11,28]. Moreover, laser surface treatment involves high heating/cooling rates and gradients which produce meta-stable phases, leading to the development of a wide variety of microstructures with novel properties that cannot be produced by any conventional processing techniques [29,30]. This may contribute to good mechanical properties and corrosion characteristics of the surface layer without affecting the bulk properties of the materials.

Many researchers have been dedicated to studying laser surface alloying on aluminum and its alloys [31,32]. Excellent coatings with high hardness, improved wear resistance and corrosion properties have been produced by laser surface alloying with optimized parameters and materials. Here, the experience of laser surface alloying is reviewed and the current situation in relation to further application assessed. The themes in this review are: laser alloying process, alloying material system, problems to be solved and future development in this field. Concluding remarks is then given after the discussion.

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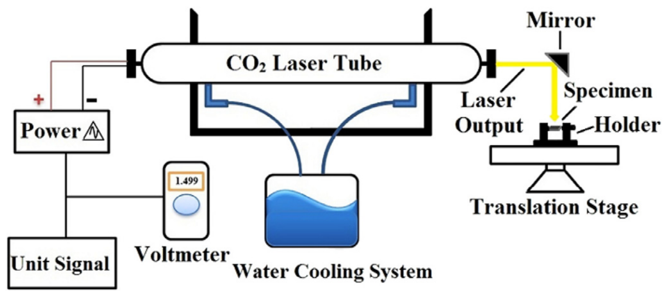

Fig. 1. Schematic diagram of experimental set-up for laser surface alloying [33].

2. Laser surface alloying process

Fig. 1 shows a schematic representation of the experimental set-up for laser surface alloying of the Al substrate surface [33]. Signal unit is designed to modulate the laser beam from pulse to continuous wave laser. The laser output is reflected by a mirror placed at an optimum distance and then irradiate on the surface of the specimen. Special moving of each specimen can be controlled through an operating system. One big difference between laser surface cladding and laser surface alloying is the mixing of coating materials with the substrate. In laser surface cladding, mixing only occurs at the coating/substrate interface or above the interface, the composition and properties of cladding materials are maintained. On the other hand, in laser surface alloying, significant mixing of the coating material with the substrate is performed to form an alloyed surface layer with new phases and compositions. The alloyed layer is generally much thinner than that of the cladded layer. At present, laser surface alloying and laser surface cladding are not strictly defined and differentiated.

2.1. Different feeding ways

Several different feeding ways are always used for laser surface alloying, including synchronous feeding way, replaced way and surface gas alloying.

In the synchronous feeding way, the consumable additions (generally in the form of powder or wire) are transported into the molten pool. Substrate and additions are melt simultaneously under the effect the laser beam, and create a metallurgical combination. This method is easy to automate, and the parameters can be conveniently controlled and adjusted. Other advantages such as low porosity, high production efficiency and good surface quality make it have a board prospect development.

In the replaced way, the consumable additions are deposited before laser treatment by using thermal spray process, electrodeposition, sol-gel, etc., and subsequently fused [34]. Appropriate shielding measures should be taken to prevent the molten pool from severe oxidation. However, the thermal spraying or electroplating is rarely used to replace the coating materials on the substrate because of the flaking caused by the residual stress in the coating layers. By far, more frequently used is the simple pre-paste powder method. The powder mixtures are mixed with polyvinyl alcohol to form a paste, and then evenly pasted on the substrate surface. This method allows the coating of complex geometries, and it is easy and inexpensive to carry out as no powder delivery system is necessary. However, the pre-paste powder on the substrate is only loosely pasted, the pasted layer could have been scratched or dropped off from the substrate surface easily. To solve this problem, Man et al. [35] developed a simple and low-cost method to monitor the process of laser surface alloying. This technique are based on the infrared emission from the melt pool using an infrared photodiode, it can distinguish the presence or the absence of the pre-paste metal powder coating, the melt depth and the dilution ratio of the alloyed layer. Even though, problems of this method still remains that the dissolution and volatilization of binder are easy to form pores in the layer, and some organic binder may pollute the surface and have a negative effect on the metallurgical bonding. Recently, a combination of sol–gel technology with laser alloying for development of coatings is a relatively new field of research [36,37]. This combined process utilizes a laser as a heat source to synthesize the sol–gel coatings and offers advantage of fast and well controlled heat input.

Surface gas alloying includes laser surface nitriding and laser surface carburizing. The method is to place the substrate in a cell filled with treatment gas or to blow the gas into the molten pool. Under the irradiation of the laser beam, the gas reacts with the melted surface to produce an alloying layer with improved properties. Several researches on surface gas alloying of soft-based metals such as titanium [38,39] and aluminum [40] has been reported. Fariaur et al. [41] created an aluminum carbide layer by excimer laser carburizing process. A cell containing methane and propylene are used to supply carbon element. A vapor plasma expands from the surface, the induced shock wave dissociates and ionizes the ambient gas. Carbon atoms diffuse into the melting surface and form an alloying layer. This aluminum carbide layer increases the wear resistance of the surface as deduced from fretting tribological tests.

2.2. Process parameters

Many factors affect the quality of laser surface treated layer [42–44]. Process parameters, such as the laser power [45], the laser beam size [46], and the scanning velocity of the laser beam [47], play a crucial role in determining the microstructures, the surface topography, and the behaviors of the alloyed zone. The effects of process parameters on microstructure and properties of the coating have been investigated and optimized to produce a desired laser alloying coating [48].

Staia et al. [34] investigated the effects of scanning velocity on A356 aluminum alloy during laser surface alloying. They demonstrated that the scanning velocity influences the extent of the laser alloyed zone, microstructural morphology and the distribution of the hard particles significantly. When scanning velocity decreases from $4\,m\,min^{-1}$ to $1\,m\,min^{-1}$, the interaction time between laser beam and metal surface increases. Both maximum depth and cross-section area of the molten pool increase. Smaller and more uniformly distributed WC particles and lager amount of compounds are obtained. The wear constant k decreases with decreasing scanning velocity, which indicates better wear resistance. Similar adhesive mechanism was observed for all samples, except those at $1\,m\,min^{-1}$. This is due to the fact that particle size of carbides decreases during a longer interaction time, the wear mechanism is changing and the aluminum matrix takes part in the transference process, lead to a more severe wear.

Similar results were observed when 2024 and 6061 Al alloys were laser surface alloyed with TiC powder under different scanning velocities [49,50]. A uniform and sound metallurgical bonding was achieved for lower velocity, but the interaction depth and the adherence of the coating decreased with increasing scanning velocity.

Yang and Hu investigated the effects of laser power density on the microstructure and microhardness of Ni−Al alloyed layer by pulsed laser irradiation [45]. The scanning velocity is $3\,mm\,s^{-1}$. Results are listed in Table 1. The depth of alloyed layer increased and the non-equilibrium phases decreased with the increasing of laser power. The alloyed layer formed at power density $5.36\times10^9\,W\,m^{-2}$ showed the least surface roughness and the highest microhardness reached to HV390.

Nath et al. [51] studied the influence of laser power on aluminum during laser surface alloyed WC+Co+NiCr. Different from previous research of Yang's [45], with increase in applied power, initially the depth of alloyed zone increased due to an increased energy absorbed, but decreased at a very high power level due to evaporation of materials from the surface. Furthermore, a comparison of Fig. 2(a) and (b) reveals that large micro-cracks are generated predominantly due to a large quenching stress when an excessive laser power is applied. The average surface