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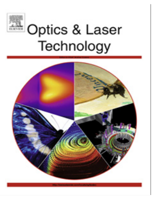

Full length article

An empirical-statistical model for laser cladding of Ti-6Al-4V powder on Ti-6Al-4V substrate

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ABSTRACT

In this article, Ti-6Al-4V powder alloy was directly deposited on Ti-6Al-4V substrate using laser cladding process. In this process, some key parameters such as laser power (P), laser scanning rate (V) and powder feeding rate (F) play important roles. Using linear regression analysis, this paper develops the empirical-statistical relation between these key parameters and geometrical characteristics of single clad tracks (i.e. clad height, clad width, penetration depth, wetting angle, and dilution) as a combined parameter ($P^{\alpha}V^{\beta}F^{\gamma}$). The results indicated that the clad width linearly depended on $PV^{-1/3}$ and powder feeding rate had no effect on it. The dilution controlled by a combined parameter as $VF^{-1/2}$ and laser power was a dispensable factor. However, laser power was the dominant factor for the clad height, penetration depth, and wetting angle so that they were proportional to $PV^{-1}F^{1/4}$, $PVF^{-1/8}$, and $P^{3/4}V^{-1}F^{-1/4}$, respectively. Based on the results of correlation coefficient ($R > 0.9$) and analysis of residuals, it was confirmed that these empirical-statistical relations were in good agreement with the measured values of single clad tracks. Finally, these relations led to the design of a processing map that can predict the geometrical characteristics of the single clad tracks based on the key parameters.

1. Introduction

Some desirable properties of Ti-6Al-4V alloy such as low density, high specific strength, high stiffness, and good combination of mechanical and chemical properties have led this alloy to be widely used in aerospace, energy and chemistry industries [1–4].

In recent years, laser cladding technology has been developed to enlarge the capability of this alloy. The material systems, which have been used in Ti-6Al-4V cladding system, have been developed from a single material to multiple materials [5–10]. Laser cladding is a process that can produce a hard layer on different substrates with minimum dilution, high density, minimum defects and strong metallurgical bond. In this process, the laser beam melts the powder particles and deposit a layer on the moving substrate [11–13]. The main process parameters are laser power (P), laser scanning rate (V), and powder feeding rate (F) that could be used as an empirical description of laser cladding technique. By analyzing laser cladding conditions, the relation between the main process parameters and geometrical characteristics should be investigated [14]. Although several authors have tried to physically model laser cladding process [15–21], it is quite complicated to provide a comprehensive description of the process due to the complex interactions in laser beam/powder/substrate system and several physical phenomena involved in laser cladding process.

Considering the complexity of physical models, empirical-statistical models based on regression methods have been developed to empirically describe laser cladding process. Davim et al. [22] predicted the geometry of clad in laser cladding process using multiple regression analysis (MRA). Through this method, the influence of the main processing parameters on the geometry of clad was investigated. Their results showed that the error associated with the geometrical form of the clad was acceptable except for the penetration depth. Saqib et al. [23] presented a model for steel powder deposition on a low carbon substrate. Their model was developed by artificial neural network (ANN) method. Nenadl et al. [24] presented a geometrical model for laser cladding process which formed by the overlap of individual tracks. Their model provided a good description of the geometrical characteristics such as clad height and clad width of single tracks for all overlapping ratios. They showed that the main process parameters could predict the geometry of the clads for both coaxial and side cladding setups. El Cheikh et al. [25] employed two kinds of models to predict the geometrical characteristics of the clads on a low carbon steel substrate. The first one was an analytical model to govern the laser clad geometry with three different distributions

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(Gaussian, uniform, and polynomial). The second model supposed that the clad's geometry governed by the surface tension and the clad was a part of a disk.

The relation between the main parameters of laser cladding and single tracks' geometrical characteristics for different powder/substrate systems have been investigated by some researchers using regression analysis [14,26–32]. However, research reports on modeling laser cladding process of Ti-6Al-4V alloy using regression analysis are limited [33–35]. Longuet et al. [33] presented a multiphase mechanical model for Ti-6Al-4V alloy. This analysis for laser-assisted processing combined a multiphase mechanical model with a metallurgical model. Crespo et al. [34] developed a thermo-kinetic laser powder deposition model in the Ti-6Al-4V system. The basis of this model is combining finite element heat transfer calculations, phase transformation kinetics, and microstructure properties. Moreover, they proposed a processing map, relating the deposition parameters to the microstructure and properties. Sun et al. [35] performed a statistical analysis and optimized the process parameters in laser cladding of Ti-6Al-4V powder on Ti-6Al-4V substrate. The proposed model was based on response surface methodology (RSM) and the model was tested by analysis of variance (ANOVA) method.

Based on the above-mentioned works, the process parameters have a great impact on the clad's geometry. All these works obtained applicable results, but there is still a lack of investigation for the relation between processing parameters and the geometry of laser cladded Ti-6Al-4V alloy. Considering the fact that Ti-6Al-4V alloy has been introduced as a promising material for additive manufacturing and multi-layer coatings and that the geometrical characteristics are very important in controlling the defect formation during the process, it is still vital to optimize the process for successful deposition of Ti-6Al-4V alloy. In regard to this, the present research aims to evaluate the relationship between the main process parameters and the geometry of laser cladded Ti-6Al-4V alloy on a substrate with a similar chemical composition so as to propose a processing map for selecting proper process parameters.

2. Material and methods

The substrate used in this study was Ti-6Al-4V alloy with the dimensions 100 mm × 100 mm × 10 mm. The surface of the substrates was grounded with sand papers before laser cladding. The morphology of Ti-6Al-4V powder (Advanced Powders and Coatings Inc., USA) is shown in Fig. 1. The nominal grain size of the powder was 90–125 μm. Table 1 presents the chemical analysis of the substrate and powder. The chemical composition of the substrate and powder were analyzed by arc spark optical emission spectrometry.

The samples were manufactured by laser cladding process with the following pieces of equipment: 700 W Nd:YAG laser system with a four-axes computer numerical controlled (CNC) machine under argon shielding environment. Table 2 shows the processing parameters in this study. After the laser cladding process, the samples were cut along the transverse direction of the single clad tracks. The specimens were grounded, polished and etched using a mixture of $17H_2O$:1HF:1HCl solution. The cross-sectional view of the specimens was investigated by field emission scanning electron microscope (FESEM; MIRA3, TESCAN; Czech Republic). Geometrical characteristics of the clads such as cladding height (h), cladding width (w), cladding angle or wetting angle (θ), and penetration depth (b) are shown in Fig. 2. Dilution ($D = b/(b + h)$) changes as the processing parameters varies [14].

For predicting the clad geometry, it was assumed that a combined parameter as $P^{\alpha}S^{\beta}F^{\gamma}$ can be used to describe each geometrical characteristic. By employing Microsoft Excel software and "trial and error" approach, the linear regression analysis is used as α, β, and γ, which can obtain the best linear fit with the highest R-squared. Eventually, a mathematical formula was introduced as $y = a(x)+b$ in which y is one of the geometrical characteristics of single clad tracks, and x is the combined parameter ($P^{\alpha}V^{\beta}F^{\gamma}$) while a and b are constants.

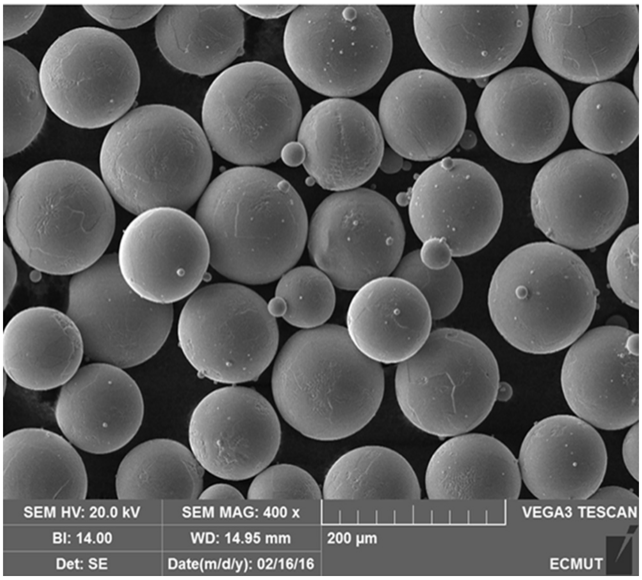

Fig. 1. SEM micrograph showing particle size and morphology of the Ti-6Al-4V powder.

3. Results and discussion

The cross section of single clad tracks at different values of P, V and F is shown in Fig. 3. Some single clads detached at laser power of 150 W. The reason can be attributed to low heat input. At high laser scanning rates, laser power is not enough to melt both the substrate and powder blowing out of the nozzle. Based on the model proposed by Jouvard et al. [36] for determining the minimum required power to melt the substrate, minimum required power has a direct relationship with the interaction time. As laser scanning rate increases from 2 to 4 mm/s, the interaction time between the substrate and laser beam decreases and consequently minimum required power to melt the substrate increases. Since laser power is relatively low, no clad could form at high laser scanning rates. On the other hand, an increase in powder feeding rate requires more energy to melt the powder. It seems that the power is not enough to melt the powder when powder feeding rate and laser scanning rate increase, simultaneously. At other laser powers, minimum power was enough to melt the substrate and powder to form a single clad. On the other hand, by increasing powder feeding rate, more powder could enter the laser beam and thus more particles are melted. It can be concluded that power had an important impact on the clad height and all three main parameters contributed to determining the clad height.

As can be seen in Fig. 3, the main parameters of laser cladding including laser power, scanning rate, and powder feeding rate are quite remarkable on the geometric properties of the clads. It can be observed that an increase in laser power increases the coating height, coating width, penetration depth, and wettability angle. In addition, laser scanning rate had a different effect on the geometrical properties. Increasing laser scanning rate reduces the clad height, increases the penetration depth, and reduces the wettability angle. Similarly, the powder feeding rate showed different effects on the geometrical properties of the clads.