Effects of Processing Parameters on Powder Utilization Ratio during Laser Metal Deposition Shaping

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Abstract. The Laser Metal Deposition Shaping (LMDS) process involves injecting metallic powder into a molten pool created by a high power industrial laser. As the laser traverses across the substrate in a layer-by-layer fashion, a fully dense metal is left in its path. A few processing parameters involved with the LMDS include the laser power, traverse speed, powder feeding rate, and gas flow rate, etc, which affect many factors of LMDS technology. Among them, the powder utilization ratio is an important one because it directly determines the build rate and build height per layer. Due to some objective reasons, the powder utilization ratio is far less than 100%. In order to ensure the stability of LMDS technology, it is necessary to investigate the match between powder utilization ratio and build rate and forming efficiency, and grasp the influence rules of processing parameters on powder utilization ratio. Accordingly, the related experiments were performed with the varied laser power, scanning speed and powder feeding rate. The results prove that the powder utilization ratio is a varied value, and affected by the processing parameters. Consequently, the relative ideal parameter match should be chosen in accordance with the specific circumstances during the LMDS technology, thus ensuring the better powder utilization ratio and promoting the forming efficiency and economic benefit.

Introduction

The Laser Metal Deposition Shaping (LMDS) process is a near-net shaping fabrication method used to manufacture metallic components directly from Computer Aided Design (CAD) files. This process involves focusing a high power laser beam onto a metallic substrate, creating a pool of molten metal. The laser beam then traverses across the substrate while metal powders are injected into the melt pool at the laser focal zone. The melting and resolidification of the added metal powder results in a fully dense metal in the wake of the moving molten pool. The process continues in a layer-by-layer fashion, until the entire component of fused metal is complete [1].

This near-net shaping production is used in rapid prototyping and rapid manufacturing for many beneficial reasons. With one step manufacturing ability, the technology can greatly reduce the lead-time and investment cost for modules and dies design, hard or rare metal components fabrication, components repair, etc [2–4]. Moreover, the as-deposited parts are fully dense, hold rapid solidified microstructure, and meet the requirements for direct usage. The technology shows extensive and promising application on many fields, such as aerospace, planes, and weapons [5,6]. However, many parameters were involved with this technological process. Among them, the powder utilization ratio is an important one because it directly determines the build rate and build height per layer. Due to some objective reasons, the powder utilization ratio is far less than 100%. In order to ensure the stability of LMDS technology, it is necessary to investigate the match between powder utilization ratio and build rate and forming efficiency, and grasp the influence rules of processing parameters on powder utilization ratio.
The powder utilization ratio is influenced by many factors. Typically, the laser power, scanning speed, and powder feeding rate are the primary processing parameters and facilitated to regulate, so they have the more obvious effects on the powder utilization ratio. The purpose of this research is to understand how the primary processing parameters surrounding the LMDS process affect the powder utilization ratio using a typical kind of metal powder.

Experimental Condition and Procedure

**Experimental Condition.** The experiments are carried out with the LMDS system which mainly consists of a 2 kW continuous wave CO₂ laser, a precisely three-dimensional numerical control working table and a powder feeder with coaxial nozzle. The powder used in the experiments is nickel-based superalloy whose composition is listed in Table 1, and the size of the powder is 200 mesh. The substrate used for multi-layer laser cladding is A3 steel plate with the dimension of 200 mm × 200 mm × 10 mm. The real photograph and schematic illustration of the LMDS system are presented respectively in Fig. 1(a) and 1(b).

| Powder                  | Chemical composition (wt.%) |
|-------------------------|-----------------------------|
| Nickel-based superalloy | C  | Al | Si | Cr | Fe | Ni |
|                         | 0.5 | 0.3 | 0.45 | 19 | 1.4 | Bal |

Fig. 1 LMDS system: (a) real photograph; (b) schematic diagram

**Theoretical Calculation Method.** The powder utilization ratio was calculated through weighing the weight difference. Supposing the weight of the substrate material is \( W_S \), the weight of the powder delivered by nozzle is \( W_P \), the total weight of the part and substrate is \( W_C \), and the powder feeding rate is \( M \), the weight of the powder sprayed by nozzle in the period of \( t \) can be described as the following formula:

\[
W_P = M \cdot t .
\]

Then, the powder utilization ratio can be expressed as:

\[
\eta = \frac{W_C - W_S}{W_P} ,
\]

while the ultimate calculation formula of powder utilization ratio can be obtained through bringing the Eq. (1) into the Eq. (2):

\[
\eta = \frac{W_C - W_S}{M \cdot t} .
\]

In this equation, \( W_C \) and \( W_S \) can be obtained by means of weighing.
**Experimental Procedure.** The experiments were performed by the multi-pass overlapping plane scanning, and the period of every experiment with a set of parameters is 60 seconds. The experiments first investigate the relationship between powder utilization ratio and scanning speed under different powder feeding rates and uniform laser powers. Then, the related experiments were carried out to study the relationship between powder utilization ratio and laser power with different scanning speeds and identical powder feeding rates. For the accuracy of experimental results, with each set of parameters, the experiments were performed twice. Then, the average value of calculating results was considered as the powder utilization ratio at this set of parameters. The main processing parameters were listed in Table 2.

| Laser power (W) | Scanning velocity (mm/s) | Powder feeding rate (g/min) | Spot diameter (mm) |
|----------------|--------------------------|----------------------------|-------------------|
| 800-1400       | 3-6                      | 6-10                       | 2                 |

**Results and Analysis**

**The Effects of Scanning Speed under Different Powder Feeding Rates.** Fig. 2 indicates the relationship between powder utilization ratio and scanning speed under different powder feeding rates and constant laser power and spot diameter. It can be seen from Fig. 2 that the powder utilization ratio shows a descending tendency with the gradual increase of scanning speed in the case of constant laser power and spot diameter. The main reason can be described as follows: The increase of scanning speed could decrease the interacting time between powder and laser in the processing place, so some powders cannot be fully melted in time. As a result, the size of generated molten pool diminishes correspondingly, which makes the amount of powder entered into the molten pool and involved in the forming process diminished. Accordingly, the powder utilization ratio shows the downward tendency.

However, this rule is likely to change under certain circumstances, since there is an optimal match between the laser power and the powder feeding rate at the constant scanning speed. As the laser power is less than or equal to the optimal match value, the variation tendency of the powder utilization ratio with the scanning speed is identical to the demonstration of Fig. 2. As the laser power is greater than that value, the contrary circumstances may appear, since the high laser power can lead to the overburning and vapourization of powder due to the high temperature. With the increase of scanning speed,...
speed, the interaction time between powder and laser will reduce at the processing position, so the chance of powder overburning and vaporization would decrease. Consequently, the powder utilization ratio would show the increasing trend. Since the laser powers performed in this study is relatively lower, the power efficiency was researched in this case.

It can be seen from Fig. 2 that as the laser power and the spot diameter keep constant, the powder utilization ratio goes down gradually with the increase of powder feeding rate. Due to the increase of powder feeding rate, the powders entered into the molten pool enhance in the unit time, but the proportion of lost powders, which cannot enter into the molten pool and be melted completely, would go up. As a result, the powder utilization ratio shows the descending trend with the increase of powder feeding rate.

**The Effects of Laser Power under Different Scanning Speeds.** Fig. 3 represents the relationship between powder utility ratio and laser power under different scanning speeds.

![Fig. 3](image)

Fig. 3 The relationship between powder utilization ratio and laser power under different scanning speeds

Fig. 3 indicates that with the increase of the laser power, the powder utilization ratio increases first and then decreases under certain powder feeding rate and spot diameter. This phenomenon proves that there is the optimal match between the laser power and the powder feeding rate. When the laser power is less than 1.2 kW, they cannot reach the optimal match. The incompletely used powders are generated since they are not melted. With the increase of laser power, the unmelted powder gradually decreases. As a result, the powder utilization ratio shows the growing tendency until the laser power and the powder feeding rate reach the optimal match. After this phase, the laser power is greater than the optimal match value, and the incompletely utilized powders produced since they are overburned. With the increase of laser power, the overburned powder could augment continuously, so the powder utilization ratio represents the decreasing trend.

**Discussion**

In addition, the powder utilization ratio is affected by other factors, such as fabricating continuity, powder feeding stability, material properties. It is necessary to control the light gate to complete the fabricating process if the as-formed parts have the complex hollow construction, thus interrupting the fabricating continuity. Moreover, the powder feeding system has the higher stability, but the practical powder feeding quantity must has the deviation with the ideal value. Furthermore, the other factors, such as material properties and spot diameter, would also lead to the change of powder utilization ratio. In general, above-mentioned factors all contribute to the calculation results of powder utilization ratio, but the experimental results still effectively reflect the powder efficiency during LMDS to some extent.
Summary
According to the experimental results, the powder utilization ratio is not a constant value. It can change with the various processing parameters. Consequently, it is suggested that the relatively ideal parameter match should be chosen in accordance with the specific conditions during LMDS, which can ensure the higher powder utilization ratio and promote the forming efficiency and economic benefit.

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