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The Temperature Effects on the Microstructure and Profile in Laser Cladding

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***Abstract*—**In this study, a 50-W CO_2 laser was used for the clad of 304L powders on the stainless steel substrate with a temperature sensor and image monitoring system. The laser power and cladding speed and focal position were modified to achieve the requirement of the workpiece flatness and mechanical properties. The numerical calculation is based on ANSYS to analyze the temperature change of the moving heat source at different surface positions when coating the workpiece, and the effect of the process parameters on the bath size was discussed. The temperature of stainless steel powder in the nozzle outlet reacting with the laser was simulated as a process parameter. In the experiment, the difference of the thermal conductivity in three-dimensional space is compared with single-layer cladding and multi-layer cladding. The heat dissipation pattern of the single-layer cladding is the steel plate and the multi-layer coating is the workpiece itself. The relationship between the multi-clad temperature and the profile was analyzed by the temperature signal from an IR pyrometer.

***Keywords*—**Laser cladding, temperature, profile, microstructure.

I. Introduction

LASER cladding has been gradually applied in the modern industry with a wide range of domains such as modification of surface's wear resistance, mold repair, and even the rapid prototyping of metal and other aspects. The process is based on moving laser heat source and melts the powder through a nozzle and deposits it on the metal plate [1].

In general, the heat affected zone and the pool in laser cladding is smaller with respect to other process methods because of its rapid cooling rate and high energy density, making it suitable for precise and miniature parts manufacturing with reducing the metal thermal deformation and the post-processing time.

Biet al. [2] found that the most efficient method of measuring the bath temperature of the cladding was to use a non-contact infrared temperature sensor. There are many ways to change the temperature of the molten pool with converting the detected infrared signal into temperature as the basis for surface quality control. However, among the laser power, the scanning of the speed, and the powder flow rate, the effect of the laser power is the most significant.

Song and Mazumder [3] studied the cladding with CCD thickness detecting method and infrared temperature sensor to measure the temperature and thickness of every cladding pass with the controller to feedback the signal, then they changed the laser power promptly online. The research shows that the clad height control is more likely to have priority than the temperature control in the processing order.

Kong and Kovacevic [4] discuss the impact on cladding height due to different laser power. The results show that, when the laser power is less than 200 W, it cannot reach the perfect connection between the powder and the substrate. However, it shows good connection between the powder and the substrate at 250 W. The cladding layer is overheated and dissolved above the 300 W laser power and the pool expand from 0.2 mm to 1.2 mm. The experiment and simulation indicated a growing trend in the temperature on the upper surface boundary and it is about 200 °C higher than the average.

He et al. [5] simulated the relationship between the laser trajectory and the maximum temperature in the case of different cladding height. The scanning trajectory was two round-trip. It was found that the workpiece temperature will keep rising during returning using a 1200 W laser. Therefore, the return path has a higher initial temperature and the difference between the first and second layers is about 200 °C. With capturing different layers' start point and midpoint, the temperature is lower in the midpoint and it is higher at the start point.

II. Experiments

A. Laser Absorption of the Powder

In this section, the temperature relationship of the 304L stainless steel powder at different particle sizes and shapes was discussed. The testing powder was classified as sphere with diameters of 15 microns, 30 microns, and non-spherical 70 microns. The powder is preset on the 0.5-mm thickness 304L stainless steel plate as shown in Fig. 1, in order to simulate the heat absorbed by different compositions of the same volume under the moving heat source.

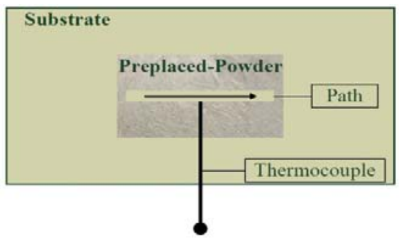

Fig. 1 Powder temperature experiment setup

The laser power is set at 50 W, the cladding speed is 20 mm/min, the laser path is 10 mm, and the thermocouple is placed at the midpoint of the laser path under the substrate. The

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data acquisition was measured by a four -channel thermometer from the left to the right end of the laser heating.

In Fig. 2, the results show that the 15-micron spherical powder has the highest temperature gradient, but most of the powder will vaporize with a rapid reduction of the radius. With the 30 microns of spherical powder, a uniform heating trend is shown. However, the actual powder temperature is several times larger than the measured value due to the measurement under the substrate. It can be found that the higher temperature can be reached with smaller powder. The irregular powder has a more compact structure than the spherical powder, e.g. the porosity of the powder stack will be smaller than the spherical powder and makes the thermal conductivity higher.

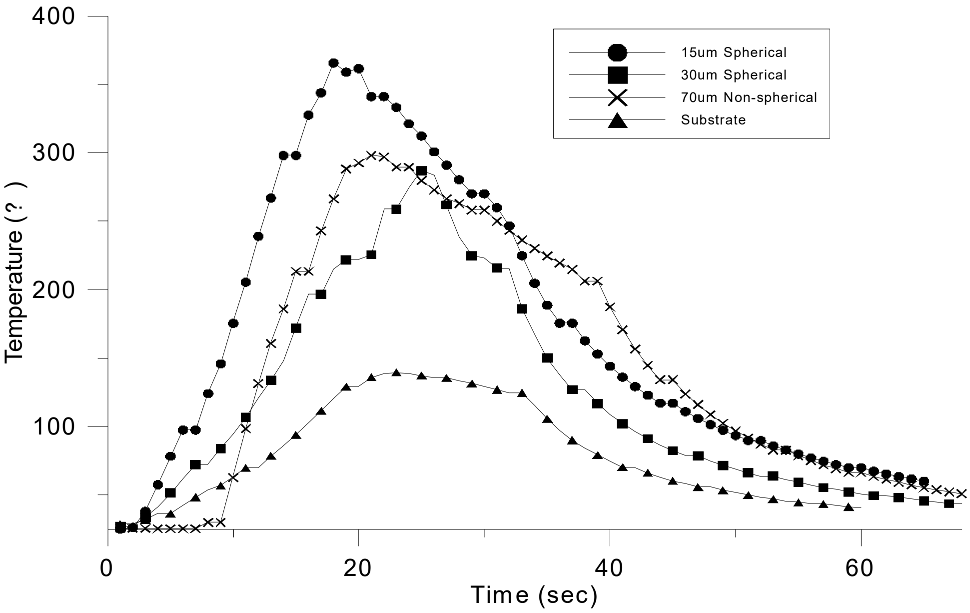

Fig. 2 Substrate changes in temperature at different preset powders

B. Powder Nozzle Adjustment with Hot Powder Observation

In order to make the laser focus coincide with the powder focal area, the position of laser focus needs to be adjusted as shown in Fig. 3.

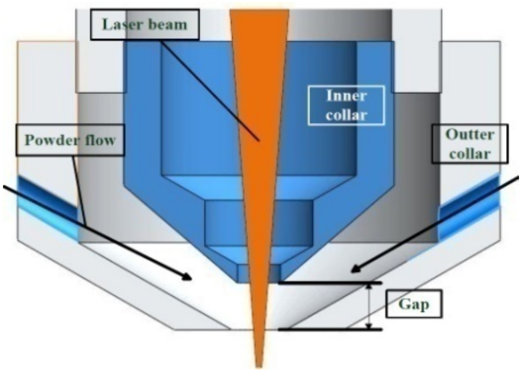

Fig. 3 Cladding nozzle drawing

It can be found that the present nozzle design will make the powder distributed from 2 mm to 4 mm at the outside nozzle axis. The ideal heating pattern is that the laser beam produces the brightest point at the focal position. With a fix gas flow and powder mass flow, the nozzle is moved to adjust the powder concentration.

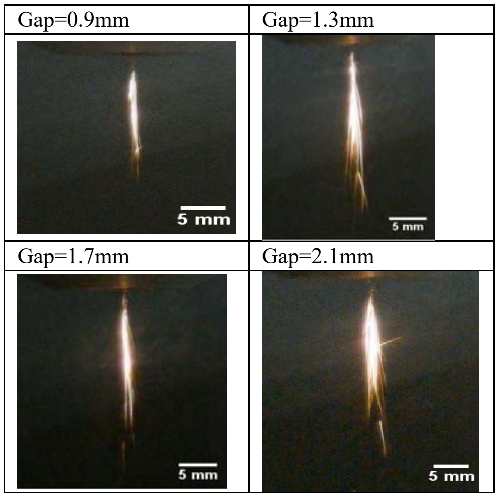

Fig. 4 Observation of the hot powder from the nozzle

The results are shown in Fig. 4, where the gap is raised from 0.9 mm to 2.1 mm. According to the flow image, it can be found that the greater the gap between the inner and outer collars of the nozzle, the longer the formation of the spark bundle. When the gas flow rate is the same, the gap controls the powder speed. The smaller the gap, the faster the powder will pass through the laser irradiation area. The powder is easier to move toward the axial position, which is the required flow pattern for deposition. However, the drawback is that the substrate and nozzle distance is too long, and it will cause a rapid attenuation of the laser beam.

Using Image J software, it can be found that laser light spot is at 15 mm as the gap of 1.3 mm as shown in Fig. 5. The metal powder axial concentration and shielding rate is lower than other parameters of processing, so this is selected in the present study.

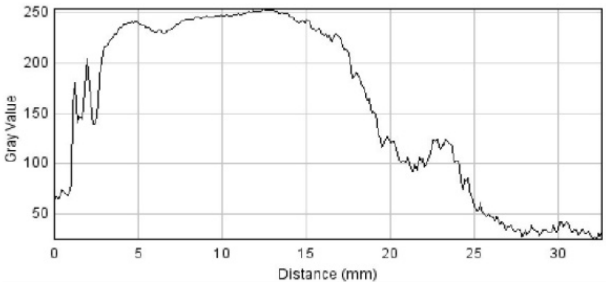

Fig. 5 The image result at 1.3 mm nozzle gap in the axial direction

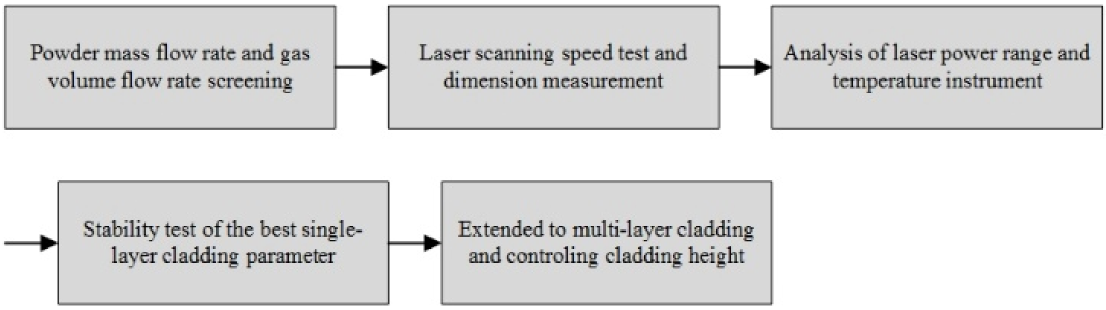

Fig. 6 Parameter testing process design

C. Single Layer Cladding

In turn of the powder mass flow rate and the laser scanning speed for the appearance, the optimum parameters as a cladding layer can be selected based on the flow chart as shown in Fig. 6. From the simulation, it can be seen that the first layer of the heat conduction has a great influence due to the thickness of the plate.

1. Powder Mass Flow Effects

The relationship between the mass flow rate of the powder and the cladding at the surface was obtained, it is necessary to control the gas flow, the feeding speed, and the powder flow rate to change the powder flow concentration.

The main parameter is the speed of powder feeder by Table I for different parameters with the laser power of 50 W and cladding speed of 10 mm/s.

TABLE I
MASS FLOW PARAMETER TEST

Parameter	Gas flow	Speed	Mass Flow Rate
A	1 L/min	300 rpm	0.018 g/s
B	1 L/min	600 rpm	0.024 g/s
C	1 L/min	900 rpm	0.034 g/s
D	2 L/min	300 rpm	0.014 g/s
E	2 L/min	600 rpm	0.018 g/s
F	2 L/min	900 rpm	0.028 g/s

The results of the single-layer cladding are shown in Fig. 7, and it can be verified from the morphology that the cases (B) and (C) with the volume flow rate of 1 L / min are shown.

Fig. 8 can be obtained after measuring the result sizes. It can be found that, in the gas flow rate of 2L/min, three groups are irregular. On the contrary, the thickness of the single-layer under the gas flow rate 1L / min will increase with the mass flow rate. It increased rapidly from 1.3 mm to 2.8 mm.

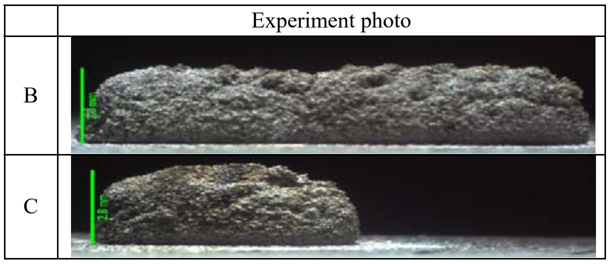

Fig. 7 Side views of the cladding at different parameters

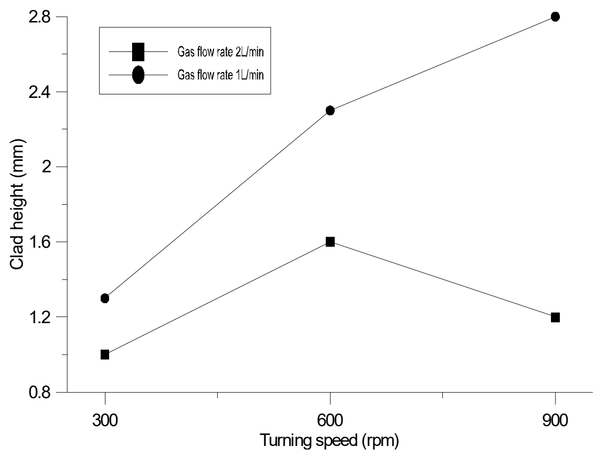

Fig. 8 Relationship between parameters and cladding height

2. Laser Cladding Speed Corresponding to the Size and Appearance

From the powder mass flow and gas flow experiments, it is observed that the different processing parameters have a huge difference in morphology. According to the previous experiment, the thickness of the first layer is about 1 mm. Since the cladding layer would be easily disintegrated if the substrate is high. For a short time of heating after the second layer, the heat will transfer to the substrate and causes re-melting and the whole-piece disintegrated. Therefore, the primary objective is to find the conditions for controlling the speed corresponding to the morphology.

TABLE II
PARAMETERS OF LASER SCANNING SPEED TEST

Parameter	Gas flow	Mass Flow	Speed
G	1 L/min	0.024 g/s	10 mm/min
H	1 L/min	0.024 g/s	15 mm/min
I	1 L/min	0.024 g/s	20 mm/min

The speed test results are shown in Fig. 9 with a laser power of 50 W and parameter in Table II. It is clear that the clad height is 2.3 mm for low-speed and 1 mm for high speed and it is inversely proportional to the cladding speed. The width decreases with the increase of the speed due to the shorter heating time.

After the laser cladding, it was found that the powder is not fully molten. Since most of the laser power is used to heat the plate, only a small amount of power is for melting, the metal powder and the powder lump are clearly visible regardless of the speed.

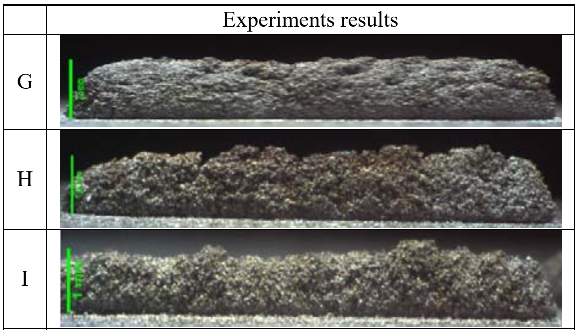

Fig. 9 Experimental results of multiple layer cladding in speed test

D. Multi-Layer Cladding Temperature Control Experiment

In the multi-layer cladding, the quality and strength can be improved by temperature control. There are many ways to change the cladding temperature. Controlling with the laser power and cladding speed, the cladding temperature and height are measured by the infrared temperature sensor and image detection system.

1. Relationship between Laser Power and Temperature

Laser cladding power is the key parameter, and it will be found that different power will correspond to different cladding morphology. The experimental parameters are selected as Table III.

The experimental results are shown in Fig. 10, it is found that the clad width is 1.2 mm with a difference that the sample only about 50% of the volume at the bottom is completely melted in the case J. The other part still maintained the sintered powder. Case K with 40 W laser power also appears to be the same situation with the fully melted specimen is at 50 W as shown in Fig. 11.

TABLE III
PARAMETER TEST OF CHANGING LASER POWER

Parameter	Power	Mass Flow	Speed
J	30W	0.024 g/s	20 mm/min
K	40W	0.024	20 mm/min
L	50W	0.024	20 mm/min

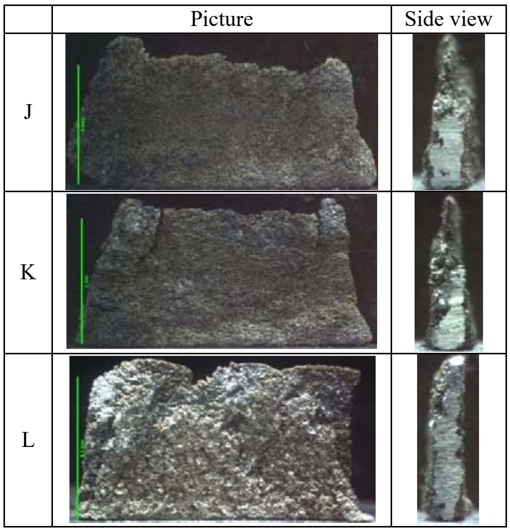

Fig. 10 Morphology and side view of six-layer cladding corresponding to different power

There are several reasons of the un-melting condition, the power shortage or the cladding speed is too high. Therefore, the heat cannot achieve the melting point.

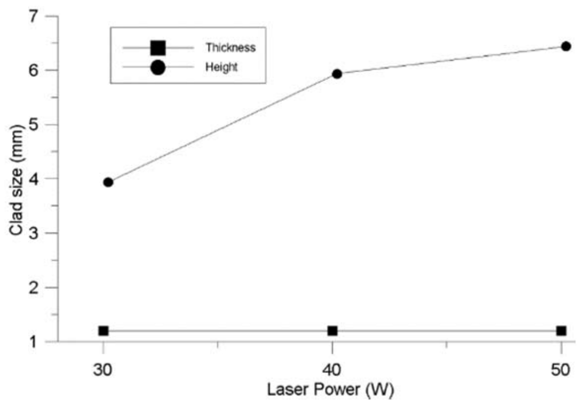

Fig. 11 Relationship between the clad height and laser power

2. Relationship between Cladding Speed and Temperature

The experiment is followed by the previous parameters, and the experimental parameters are shown in Table IV.

As a result, if the speed is more than 30 mm/min, the powder is difficult to melt on the surface, the lack of adhesion leads to uneven morphology.

TABLE IV
PARAMETER OF CLADDING SPEED TEST

Parameter	Power	Mass Flow	Speed
M	50W	0.024 g/s	20 mm/min
N	50W	0.024 g/s	25 mm/min
O	50W	0.024 g/s	30 mm/min

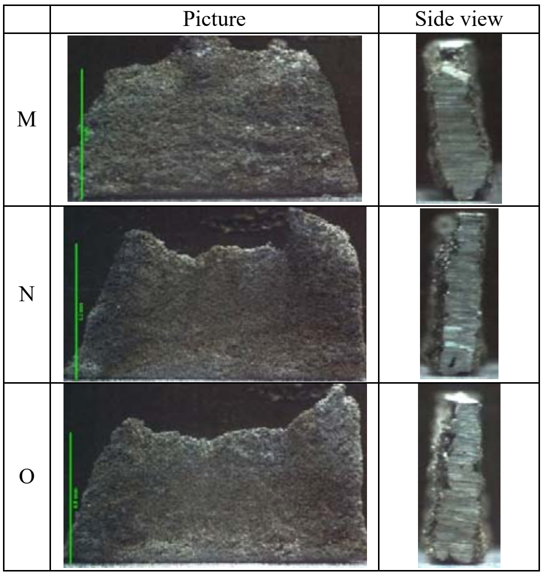

Fig. 12 Different morphology and side view of six cladding corresponding to different speeds

In Fig. 12, it can be seen that both the cladding appearance and size are remarkably changed with the speed. As expected, the clad height and the width increase when the speed decreases. The tendency is shown in Fig. 13. The cladding quality still remains good at the speed of 30 mm/min.

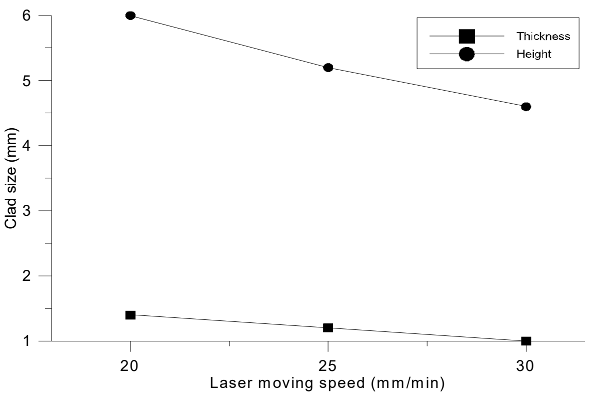

Fig. 13 Profile size and speed relationship

E. Microstructure Testing

Microstructure examination of 304L stainless steel cladding samples is prepared as shown in Fig. 14. In Fig. 15, the speed is increased from 20 mm/s to 30 mm/s. In terms of metallurgical microstructure, martensite gradually transformed from small grains into a coarser austenite structure. Because the heat gradually reduced, it is not enough to reach the metamorphosis temperature. The degree of grain refinement can affect the hardness, and it will block the sliding mechanism.

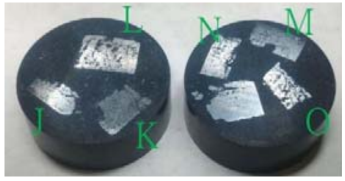

Fig. 14 Metallographic specimen

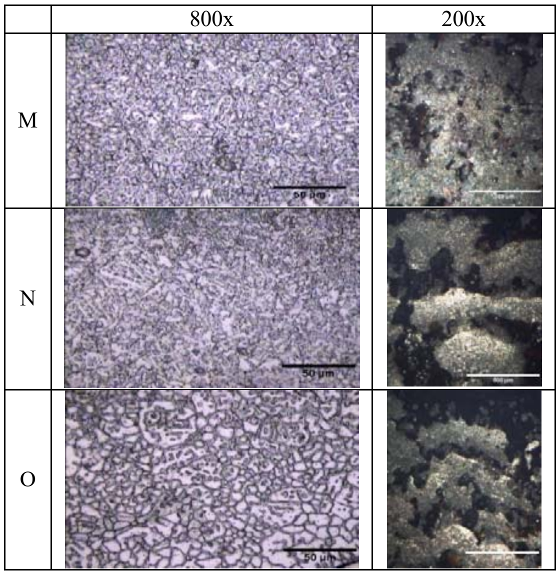

Fig. 15 Microstructure at different layer

III. CONCLUSION

When the cladding is vertically built from the substrate, the heat of the following layer has been transferred to the workpiece. When the cladding speed is less than 20 mm/min, a large amount of powder will be deposited on the workpiece, forming a clad of about 2 mm width. Therefore, changing speed from 20 mm/min to 30 mm/min, the powder from insufficient adhesion can be avoided.

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