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# Study on Laser Consolidation of Metal Powder with Yb: fiber laser - Temperature Measurement of Laser Irradiation Area -

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The layered manufacturing technique is one of the most effective processes for the manufacture of prototypes, tools and functional end products. Selective Laser Sintering (SLS) and Selective Laser Melting (SLM), in particular, are two of the most versatile techniques, able to cover a wide range of materials such as polymer, ceramic and metal powder. In this study, the monitoring method of processing temperature at laser irradiation area by two-color pyrometer is applied. In order to investigate the consolidation characteristics of chromium molybdenum steel (SCM) based powder with a Yb: fiber laser, the maximum temperature at the irradiation area of a laser beam was measured under various experimental conditions. The influence of the scan conditions of a laser beam on the maximum temperature was evaluated. As a result, it was revealed that the maximum temperature during laser irradiation changed under the influence of laser power and scan speed of a laser beam. The maximum temperature increased with the increase of laser power, and decreased rapidly to almost at room temperature for 20 ms after the laser beam passed the center of the target area. More than the unit length 5 mm, the maximum temperature during laser irradiation was not influenced by the previous laser scan.

**Keywords:** Yb: fiber laser, rapid tooling, chromium molybdenum steel powder, consolidation material, two-color pyrometer, maximum temperature measurement

## 1. Introduction

The layered manufacturing technique is one of the most effective processes for the manufacture of prototypes, tools and functional end products. Various techniques, such as Stereolithography (SLA) with photo polymerization of liquid polymer, Fused Deposition Modeling (FDM) with solidification of molten polymer and Laminated Object Manufacturing (LOM) with sheet stacking processes, have been applied to date for the achievement of manufacturing objectives. Selective Laser Sintering (SLS) and Melting (SLM), in particular, are two of the most versatile techniques, able to cover a wide range of materials. Recently, a multifunction machine, by which ferrous based powder bed is selectively melted by laser beam and the edge of the consolidation layer is cut with an endmill, has been developed to produce injection molding die for the purpose of reducing manufacturing time and cost[1]. In this device, a variety of ferrous based powder melting and sintering conditions are used to obtain a high quality layered model. The superfluous supply of generated heat causes the evaporation of ferrous based powder, and insufficient supply results in inadequate consolidation. Therefore, the quality of the layered model is greatly influenced by the irradiation condition of the laser beam and the generated heat of irradiation.

In this study, the monitoring method of processing temperature at laser irradiation area by two-color pyrometer, which has been developed by the authors, is applied. In order to investigate the consolidation characteristics of chromium molybdenum steel (SCM) based powder with a Yb: fiber laser, the maximum temperature at the irradiation area of a laser beam was measured under various experimental conditions. The influence of the laser power and unit length of laser scan on the maximum temperature was evaluated.

## 2. Experimental method

### 2.1 Temperature measurement

In this experiment, a two-color pyrometer which was developed by the authors was used. It has almost the same structure shown in the authors' previous papers [2-5]. The fundamental structure of the two-color pyrometer is shown in Fig.1. The pyrometer is composed of an optical fiber and two types of infrared detector; namely, an InAs detector and an InSb detector. The InAs detector was mounted in a sandwich configuration over the InSb detector, with each detector having a different range of acceptable wavelength. The laser beam cannot reach these detectors by using a Germanium optical filter, the characteristic of which is that it does not transmit less than 1.6  $\mu\text{m}$  in wavelength. The infrared energy radiated from an object is accepted by a

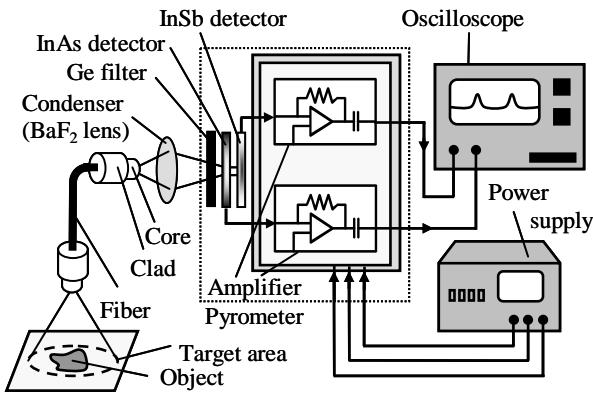


Fig.1 Fundamental structures of InAs-InSb pyrometer

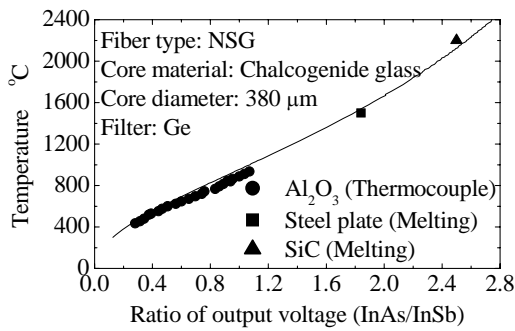


Fig.2 Calibration curve

chalcogenide optical fiber and led to a two-color detector. It is converted into an electric signal and stored in digital memory. By taking the ratio of these two output voltages and using a calibration curve, the temperature at the irradiation area of the laser beam can be obtained.

### 2.2 Calibration of the pyrometer

The calibration was carried out using two different methods. In the range up to 1000 °C, the known uniform temperature on a radiation surface was measured with a thermocouple. Alumina was used as a workpiece. In the range exceeding 1000 °C, the minimum output detected from the melt surface was measured during laser irradiation. SiC of 2200 °C in sublimation point and steel plate of 1510°C in melting point were used as a workpiece [6-8]. The steel plate used is a cold rolled steel (JIS SPCC) and its thickness is  $t=3.2$  mm. The surface roughness of this steel plate is  $Ra=0.6$   $\mu\text{m}$ . Fig.2 shows the calibration curve obtained. The solid line in the graph is the curve derived from the theoretical sensitivity of the pyrometer. The experimental points coincided well with the calculated curve. Therefore, the conversion to temperature is calculated with the theoretical curve.

### 2.3 Experimental procedure

The experimental arrangement is schematically illustrated in Fig.3, and specifications of laser beam are shown in Table 1. The consolidation system was composed of a Yb: fiber laser (SUNX Ltd.: LP-F10) and a consolidation unit of a metal powder. The metal powder was mainly composed of chromium molybdenum steel, and its mean di-

Table 1 Specifications of laser beam

Laser type	Yb: fiber (CW)
Beam diameter	$\phi$ 45 $\mu\text{m}$
Wavelength	$\lambda$ 1070 nm
Maximum power	$P$ 40 W
Scanning speed	$F$ 1-3000 mm/s

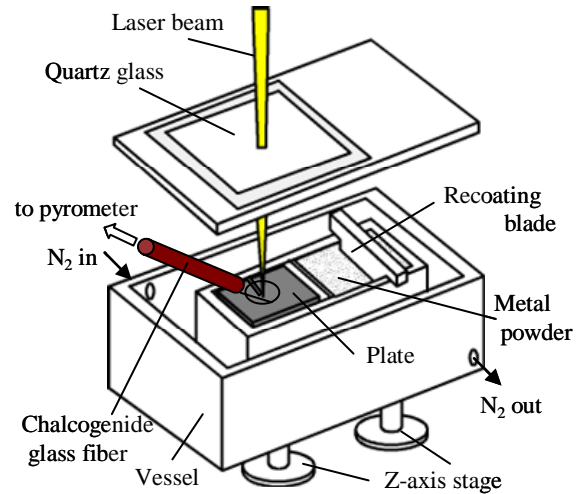


Fig.3 Schematic illustration of experimental arrangement

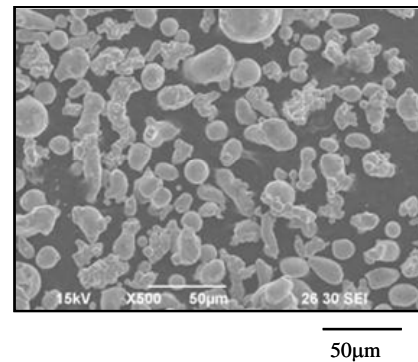


Fig.4 SEM image of metallic powder ( $d=25\mu\text{m}$ )

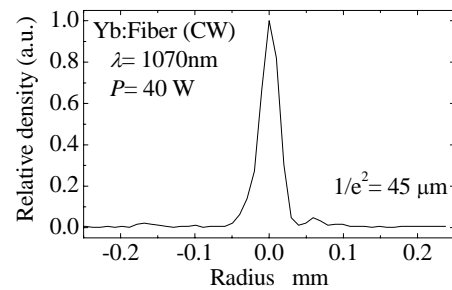


Fig.5 Profile of the laser beam

ameter was  $d=25$   $\mu\text{m}$  as shown in Fig.4. This powder was deposited on the plate so that its thickness was fixed with a recoating blade. Since that the deposited powder surface was loaded under gravity action only, its bulk density was 4300  $\text{kg}/\text{m}^3$  [9]. The laser beam, whose wavelength is

Table 2 Experimental conditions

Laser power	$P$	10 - 40 W
Scanning speed	$F$	19 - 180 mm/s
Hatching pitch	$H$	25 - 100 $\mu\text{m}$
Layer thickness	$t$	50 $\mu\text{m}$
Particle size	$d$	25 $\mu\text{m}$
Layers number	$n$	1 layer

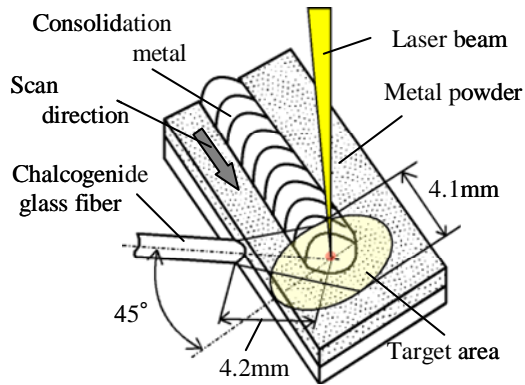


Fig.6 Enlargement of irradiation area at line consolidation

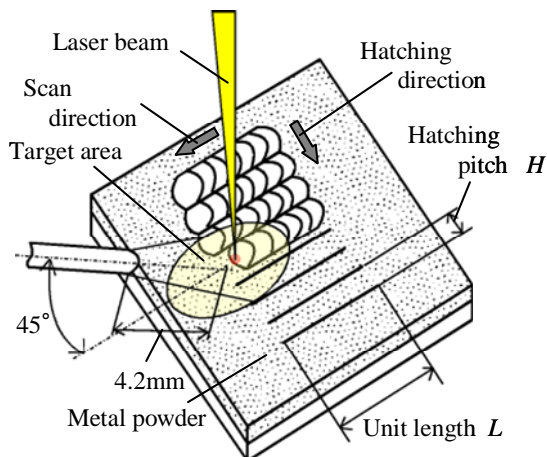


Fig.7 Enlargement of irradiation area at area consolidation

$\lambda=1070$  nm, was irradiated to the surface of the fixed powder through a galvanometer mirror at the focus spot. Fig.5 shows the intensity relative density of laser beam measured by beam profile system (OPHIR Corp.: Beam star FX-50). The laser beam formed a Gaussian shape and the diameter at the focus spot was  $\phi=45$   $\mu\text{m}$ . The vessel for consolidation was filled up with nitrogen so as to prevent the oxidation of the metal powder during the laser irradiation.

#### 2.4 Experimental method at line consolidation

The schematic enlargement of the laser irradiation area is shown in Fig.6, and the experimental conditions are shown in Table 2. A fiber was set at a distance of 4 mm from the laser area and at an angle of  $45^\circ$  from the optical axis. The center of the laser area always passed on the center axis of the fiber. Therefore, the fiber could receive the infrared rays radiated from the laser spot when the laser beam passed inside of the target area of the fiber. A chal-

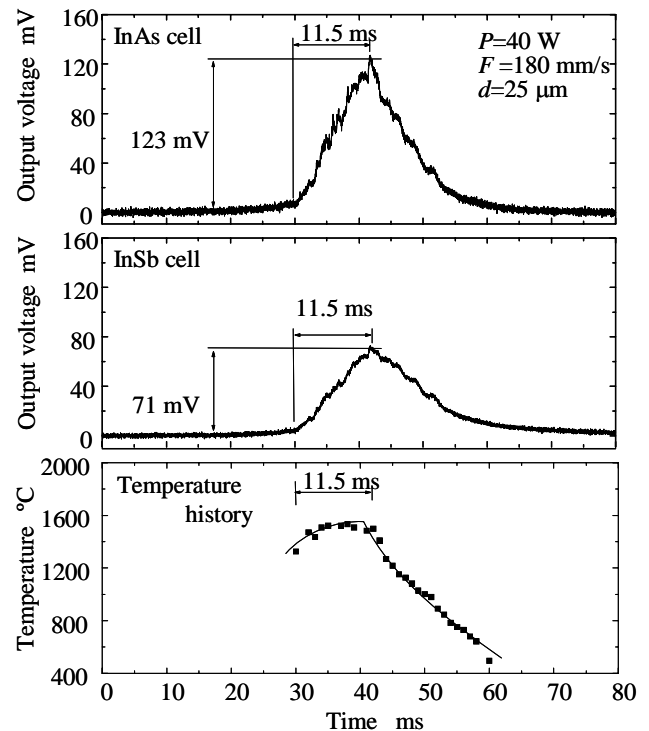


Fig.8 Recorded output waves of pyrometer

cogenide optical fiber whose diameter was  $\phi_f=380$   $\mu\text{m}$  and whose acceptance angle was  $24^\circ$  is used. Therefore, the distance passed inside of the target area was 4.1 mm.

Metal powder was constantly deposited on the consolidation plate at a thickness of 50  $\mu\text{m}$ . A cold rolled steel (JIS SPCC) whose thickness was  $t=3.2$  mm was used as a consolidation plate. In order to improve the wetting property of the molten powder, the plate surface was finished by sandblast which was #35 in average grain size. The surface roughness of the finished plate was  $Ra=3.5$   $\mu\text{m}$ . The maximum temperature at the irradiation area was measured under various experimental conditions. The influence of the scan conditions on temperature was evaluated.

#### 2.5 Experimental method at area consolidation

The enlargement of the laser irradiation area is schematically shown in Fig.7, and the experimental conditions are shown in Table 2. The irradiated laser beam was scanned on the deposited surface of the metal powder at equal unit length  $L$  and hatching pitch  $H$ . A chalcogenide optical fiber was set so that the center of the target area was fixed at the end point of the laser scan position. The distance between the fiber tip and the end point of the laser scan position was 4.2 mm. The fiber was set at an angle of  $45^\circ$  from the optical axis.

Metal powder was also deposited on the plate at a thickness of 50  $\mu\text{m}$ . To investigate the effects of the unit length and the hatching pitch on temperature, the maximum temperature when the laser beam passed through the target area was evaluated.

### 3. Results and discussion

#### 3.1 Output wave of pyrometer

Fig.8 shows the typical output profiles for the pyrometer under the condition of  $P=40$  W and  $F=180$  mm/s. The

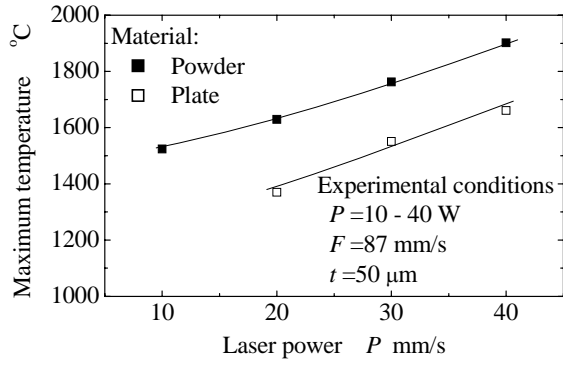


Fig.9 Influence of laser power on maximum temperature

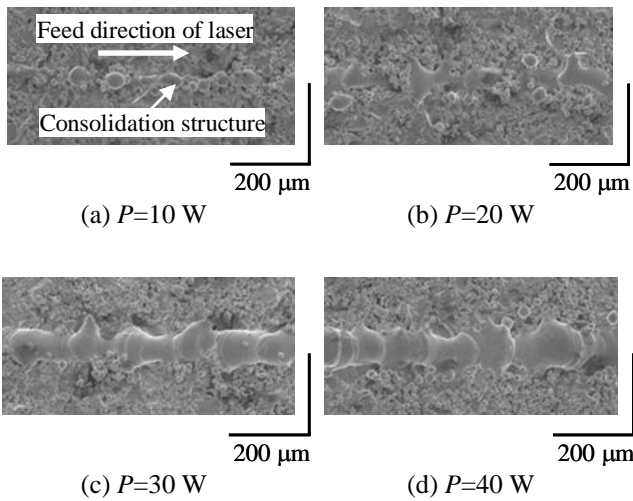


Fig.10 SEM image of consolidation structure

upper two figures represent the output voltages of two detectors and the lowest figure represents the temperature obtained from these. When the laser beam reached the target area of the pyrometer, the infrared energy generated by the laser irradiation was immediately detected by each detector and converted into the electric signal. The output signals increased as the laser beam approached the center of the target area, and these signals were the maximum value when the laser beam reached the center. Then, these signals decreased rapidly after the laser beam passed the center. The variation of the temperature obtained by taking the ratio of the output signals showed the similar trends with that of the output signals obtained from two detectors, i.e. the temperature obtained was the maximum when the laser beam reached the center of target area. From these results, it showed that the laser beam was not detected in each detector by cutting off with a germanium filter and the pyrometer could measure the temperature of the laser area without being affected by the reflected laser beam.

### 3.2 Effect of laser power on the maximum temperature

The variation of laser power with the maximum temperature under the conditions of  $F=87$  mm/s and  $t=50$   $\mu$ m is shown in Fig.9, and its SEM images are shown in Fig.10. The maximum temperature on the consolidation plate

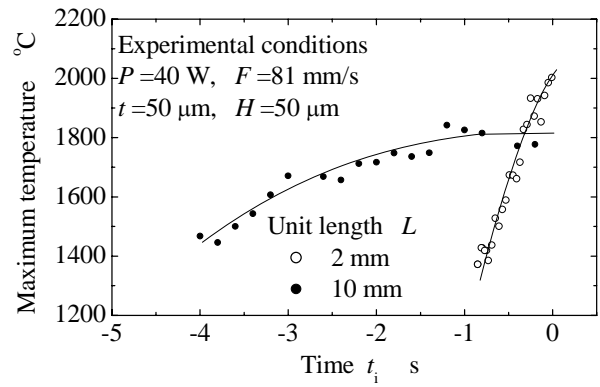


Fig.11 Temperature history in each length

without powder was also measured for comparison. The plate surface was finished by sandblast which was #35 in average grain size and its surface roughness was  $Ra=3.5$   $\mu$ m. The maximum temperature increased greatly with the increase of laser power in each material. The maximum temperature of the powder was 1500  $^{\circ}$ C at a laser power of  $P=10$  W, and increased to 1900  $^{\circ}$ C at  $P=40$  W. It was clear that the influence of laser power on the maximum temperature was considerable. On the other hand, the maximum temperature on the molten powder was about 200  $^{\circ}$ C higher than that on the consolidation plate under all experimental conditions. This is due to the thermal conductivity of the deposited metal powder, i.e. the thermal conductivity of metal powder was 0.14 W/(m $\cdot$ K) and quite smaller than that of the consolidation plate of 56 W/(m $\cdot$ K) [6,8]. The generated energy by the laser irradiation on the surface of the deposited metal powder was not circumferentially diffused, and resulted in the rise of the maximum temperature.

The form of the solidified powder on the consolidation plate was quite different under each condition. The structure formed was spherical at a laser power of  $P=10$  W, and became linear with an increase in laser power. The width of structure became wide with an increase of laser power. This was because of the absorbed energy to the powder increased with the increase in laser power, and then the melted area was enlarged. From these results, it showed that the maximum temperature of the laser irradiation area was related to the consolidation aspects of the solidified metal powder. In this case, the temperature ranges to consolidate the molten powder linearly were from 1750  $^{\circ}$ C to 1900  $^{\circ}$ C. Therefore, it was shown that the consolidation characteristics could be controlled by monitoring the maximum temperature of the laser irradiation area.

### 3.3 Effect of unit length on the maximum temperature

Fig.11 shows the history of the maximum temperature obtained by taking the ratio of the output signals from two detectors under the conditions of  $P=40$  W,  $F=81$  mm/s,  $t=50$   $\mu$ m and  $H=50$   $\mu$ m. The maximum temperature which passed through the target area of the pyrometer in each unit length was recorded. The position at  $t_i=0$  is where the laser beam passed through the center of the target area of the pyrometer. When the unit length was  $L=2$  mm, the maximum temperature in each unit length increased as the laser beam approached the center of the target area, and reached

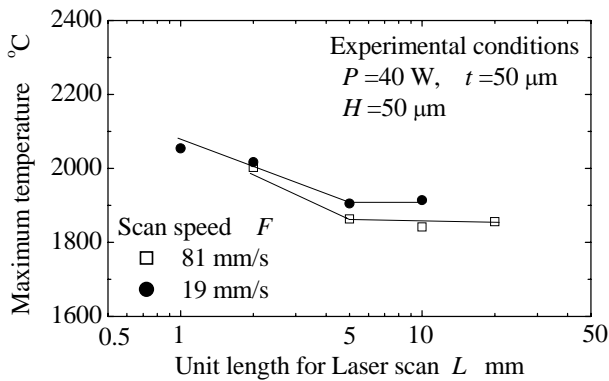


Fig.12 Effect of unit length on maximum temperature

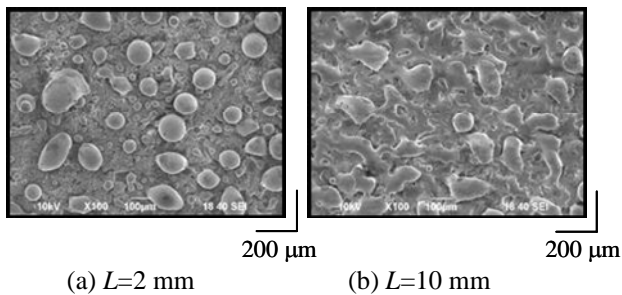


Fig.13 SEM image of consolidation structure ( $P=40\text{ W}$ ,  $F=81\text{ mm/s}$ )

the maximum value when the laser beam was located at the center. On the other hand, when the unit length was  $L=10\text{ mm}$ , the maximum temperature increased gradually and was almost constant around the center of the target area. In addition, the maximum temperature of  $L=10\text{ mm}$  was about  $1800\text{ }^{\circ}\text{C}$ , and  $200\text{ }^{\circ}\text{C}$  lower than that of  $L=2\text{ mm}$ . These results indicated that the maximum temperature at the laser irradiation area was related to the unit length for laser scan. The time interval to which the laser beam was irradiated was short under the condition of  $L=2\text{ mm}$ , so that the maximum temperature increased greatly compared to  $L=10\text{ mm}$ . Fig.12 shows the variation of the maximum temperature on the deposited powder surface with the unit length for laser scan under the conditions of  $P=40\text{ W}$ ,  $t=50\text{ }\mu\text{m}$  and  $H=50\text{ }\mu\text{m}$ . The scan speed of the laser beam was  $F=19\text{ mm/s}$  and  $F=81\text{ mm/s}$ . The maximum temperature decreased in the range up to  $L=5\text{ mm}$ , and this value remained constant in the range exceeding  $L=5\text{ mm}$ . There was no effect of the scan speed on the maximum temperature. It was also shown that the maximum temperature was influenced with the unit length of laser scan.

Fig.13 shows the SEM images of the consolidation structure under the conditions of  $P=40\text{ W}$  and  $F=81\text{ mm/s}$ . As shown in Fig.13 (a), the structure formed under the unit length of  $L=2\text{ mm}$  was spherical and the consolidation plate was observed. This is because the superfluous energy was absorbed to the deposited powder surface and the melt pool was enlarged due to surface tension and shrinkage. The maximum temperature in this condition was  $2000\text{ }^{\circ}\text{C}$ . On the other hand, as shown in Fig.13 (b), when the unit length was  $L=10\text{ mm}$ , the consolidation surface was smooth compared with the condition of  $L=2\text{ mm}$ . This result indicated

that the absorbed energy to the deposited powder is moderate for consolidating the molten powder. The maximum temperature in this condition was  $1850\text{ }^{\circ}\text{C}$ . This result was almost same as the maximum temperature obtained in Fig.9. From these results, we were able to obtain the consolidation structure without an inhomogeneous defect through the laser irradiation with the unit length exceeding  $L=5\text{ mm}$ . Moreover, the quality of the consolidation structure could be controlled by monitoring the temperature at the laser irradiation area.

#### 4. Conclusions

The monitoring method of processing temperature at laser irradiation area by two-color pyrometer was applied, and the maximum temperature at the irradiation area was measured under various experimental conditions. The main results obtained are as follows:

- (1) The output signals from the pyrometer were detected as the laser beam approached the center of the target area, and these signals were the maximum value when the laser beam reached the center. Then these signals decreased rapidly after the laser beam passed the center.
- (2) The pyrometer could measure the maximum temperature of the laser irradiation area without being affected by the reflected laser beam.
- (3) The maximum temperature on the deposited powder surface was greatly influenced with the laser irradiating conditions such as the laser power and unit length for laser scan, and was related to the consolidation aspects of the solidified metal powder.
- (4) The quality of the consolidation structure could be controlled by monitoring the maximum temperature at the laser irradiation area. This structure without inhomogeneous defects was obtained with a unit length exceeding  $L=5\text{ mm}$ .

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