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Study on laser consolidation of metal powder with Yb:fiber laser—Evaluation of line consolidation structure

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A B S T R A C T

This study describes the consolidation characteristics of chromium molybdenum steel (SCM) based powder used for rapid tooling. The laser beam used was a Yb:fiber laser with a spot diameter of 45 μm and a maximum power of 40 W. In order to investigate the influence of irradiation conditions on the maximum temperature at the focal area, a two-color pyrometer developed by the authors was used. In addition, the cross section of the consolidated structure was analyzed with an electron probe microanalysis, and the cutting force was measured with a dynamometer. The result showed that the maximum temperature at the focal area was related to the consolidation characteristics of the metal powder. The main parameters which affected the consolidation characteristics were laser power and scan speed of the laser beam. The deposited powder and the plate surface were melted with generated heat and alloyed in the process of the solidification. The specific cutting force was greatly influenced by the consolidation conditions. The highest value of a specific cutting force was obtained when the melting of the powder and the solidification of the molten powder were performed repeatedly and the structure was consolidated linearly.

1. Introduction

Since Kodama (1981) presented a new method for the automatic fabrication of a three-dimensional plastic model, various types of layered manufacturing techniques have been proposed, such as fused deposition manufacturing, selective laser sintering and laminated object manufacturing (Kruth, 1991). The layered manufacturing technique has been followed with the development of three-dimensional CAD systems, and classified as a different new group from the forming process and the material removal process (Kruth, 1991). A variety of components, such as polymer, ceramic, paper and metal powder, have been applied to date for the achievement of manufacturing prototypes, tools and functional end products. The development of the layered manufacturing technique with metal powder is especially remarkable because practical use is possible for the obtained products. Powder consolidation is classified into several types of mechanisms. These are: Solid State Sintering, Liquid Phase Sintering, Full Melting and Chemical Induced Binding (Lu et al., 2001). These types are mainly classified by the energy density at laser beam irradiation. When the energy supplied to the powder is insufficient, a consolidation process occurs below the melting point of the powder, and necks between adjacent powders occur (Tolochko et al., 2003). This phenomenon is defined as Solid State Sintering and post-processing of the consolidated structure is needed. When the laser energy supplied to the powder increases, the melting of powder surface occurs, which is defined as Liquid Phase Sintering (Fischer et al., 2002), and further increase of laser density fully melts the metal powder (Kruth et al., 2003).

Recently, a multifunction machine, in which a ferrous based powder bed is selectively heated and fused by a laser beam irradiation and the edge of the consolidated structure obtained by a few layered manufacturing processes is cut with an end mill, has been developed to produce an injection molding die with a low cost and a short time (Abe et al., 2006). In this device, a CO_2 laser beam with a diameter at the focal area of 0.4 mm is used, and the consolidated structures via Liquid Phase Sintering and Full Melting are obtained. However, this device has problems which should be solved about the accuracy of the obtained structure associated with the laser beam diameter and the absorbency to metal powder.

In this study, the consolidation characteristics of ferrous based powder with a Yb:fiber laser beam with a spot diameter of 45 μm was investigated. The maximum temperature at a laser irradiation area was measured with a two-color pyrometer, and the influence of laser power and laser scan speed on the maximum

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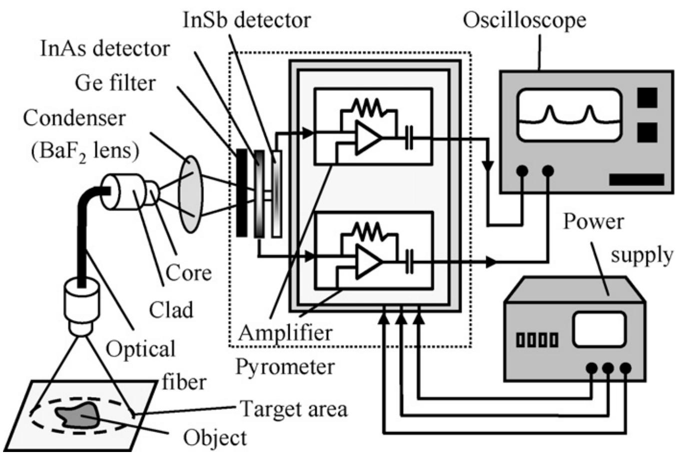

Fig. 1. Fundamental structure of two-color pyrometer.

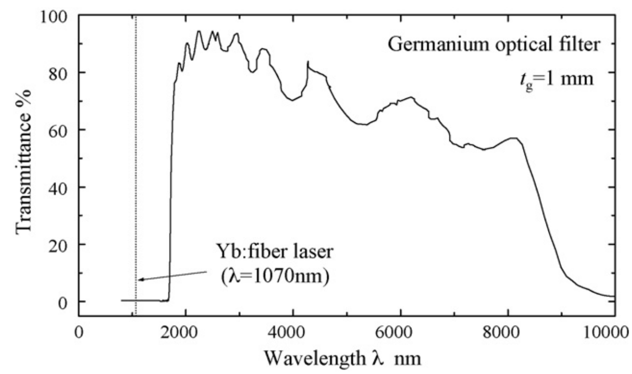

Fig. 2. Transmittance of germanium optical filter.

temperature was evaluated. The cross section of the consolidated structure was analyzed with electron probe microanalysis. In addition, the specific cutting force is measured with a dynamometer in order to estimate the aspect of the consolidation under various conditions.

2. Temperature measurement

2.1. Two-color pyrometer

Ignatiev et al. (1996) had reported about the real-time monitoring of the surface temperature on metallic materials during laser beam irradiation with two silicon photo diodes. In this paper, different types of detectors are used to measure the maximum temperature during laser beam irradiation. The fundamental structure of a two-color pyrometer is shown in Fig. 1. The pyrometer was composed of an optical fiber and two types of infrared detectors; namely, an InAs detector and an InSb detector. The optical fiber used was a chalcogenide glass with a core diameter of $\phi = 380\,\mu m$ and an acceptable wavelength from 1 μm to 6 μm. The InAs detector was mounted in a sandwich configuration over the InSb detector, with each detector having a different range of acceptable wavelength. Thus, the InAs detector responded to radiation from 1 μm to 3 μm and transmits waves larger than 3 μm, while the InSb detector responded to radiation from 3 μm to 5.5 μm. The infrared energy was converted to an electric output signal, amplified and stored in a digital memory. The InAs pyrometer had frequency characteristics with a flat response from 10 Hz to 400 kHz (Ueda et al., 2001). The sampling time of the two-color pyrometer used was 1 μs, and it had enough speed to measure the laser irradiation area. By taking the ratio of output signals, the influence of the emissivity occurring in the surface characteristics at the laser irradiation area is eliminated (DeWitt and Nutter, 1988; Childs and Childs, 2001).

The energy accepted by the pyrometer can be calculated theoretically on the assumption that the object has a blackbody surface at uniform temperature and there are no losses at all. It has been shown in the author's previous paper that the energy does not depend on the distance between the optical fiber tip and object (Ueda et al., 1985, 1995). Hence, the temperature measured by a two-color pyrometer does not depend on the size of the target area.

To protect the two-color pyrometer from laser irradiation, a germanium optical filter with a thickness of 1 mm was applied. Its transmittance with the wavelength which was measured by infrared spectrometer (PerkinElmer: Spectrum One NTS) is shown in Fig. 2. As was obvious from the graph, the germanium optical filter could cut off almost all wavelengths below λ = 1600 nm. The wavelength of the Yb:fiber laser beam used was λ = 1070 nm. Therefore, the laser beam reflected on the powder surface did not reach these detectors. In addition, it was confirmed that the laser beam was not detected by the two-color pyrometer even if the laser beam was directly irradiated to the chalcogenide glass fiber tip.

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, as shown in Fig. 3. Alumina was used as a work material. In the range exceeding 1000 °C, the minimum output, at which the surface of the specimen melted when the laser beam was irradiated, was measured. As work materials, SiC with a melting point of 2200 °C and a steel sheet with a point of 1510 °C were used. The surface roughness was *Ra* = 0.18 μm for the SiC and *Ra* = 1.7 μm for the steel sheet, respectively. The SEM image of the silicon carbide surface is shown in Fig. 4. Before the surface was melted by laser irradiation as shown in Fig. 4(a), thermal damage corresponding to a spot diameter was formed on the surface. Fig. 4(b) gives the formation of the heat affected zone after the surface was melted. Hence, the minimum laser irradiation condition which formed the heat affected zone as shown in Fig. 4(b) was measured as a melting temperature of the specimen.

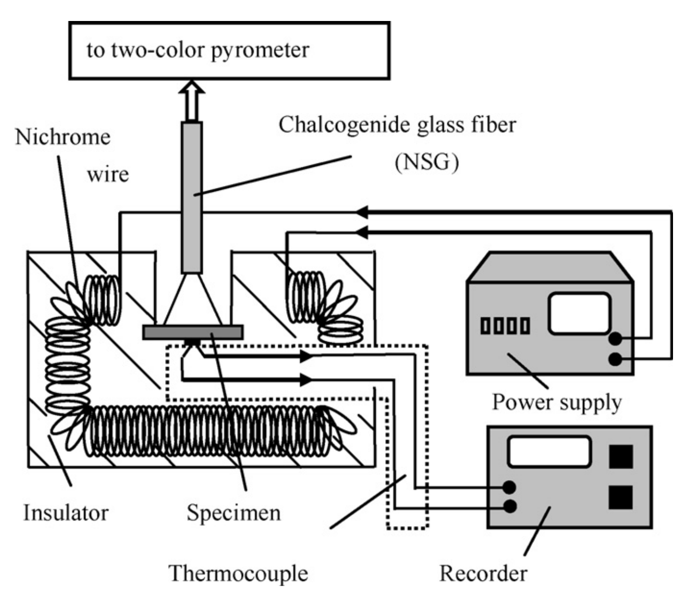

Fig. 3. Schematic illustration for calibration of pyrometer.