Freeform Fabrication of Aluminum Alloy Prototypes Using Laser Melting

Hideki KYOGOKU[1], Masashi HAGIWARA[2], and Toshifumi SHINNO[1]
[1] Faculty of Engineering, Kinki University
Higashihiroshima, Hiroshima 739-2116 Japan
[2] Aspect Inc.
Inagi, Tokyo 206-0802 Japan

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Abstract

In this study, a direct selective laser sintering/melting machine was designed and constructed. The machine has a 50 W Yb-fiber laser, a galvanometer scanner and a powder delivery and build system. It was confirmed that the machine works well. The fabrication conditions of aluminum alloys were investigated using the machine. The optimum laser power, scan speed and scan pitch were investigated by experiments. The effect of addition of metal powder as additives on laser scanning process was investigated to fabricate the sound laser-scanned body of aluminum alloys based on Al-12Si alloy. It was found that the smooth single-scan track can be fabricated at lower laser power and higher scan speed by the addition of a laser absorption material. An aluminum alloy prototype was successfully produced using optimum laser scanning conditions.

Introduction

Selective laser sintering/melting has been widely utilized as one of the RP processes of various materials such as polymers, metals and ceramics. In the field of automotive industries especially, the RP process has been introduced to develop a new car as fast as possible. Also it is necessary for recent new cars to be designed and manufactured with light weight to save energy. Therefore, the application of aluminum alloys has increased in automotive parts. The RP technology, however, is not able to manage well to produce trial products of aluminum alloy. The authors developed a laser sintering/melting machine which can fabricate metal products, in particular aluminum alloy and titanium alloy products, with high density and high accuracy, against the background of development of high performance fiber-laser and alloy powders in the project. Simultaneously, some companies developed commercialized machines. The features of these machines are using a fiber-laser to fabricate high accuracy products and having a chamber to keep a vacuum atmosphere.

Recently, research on the RP process of aluminum alloys has been reported. Sercombe *et al*. [1-3] reported on the fabrication of a resin-bonded aluminum alloy part using selective laser sintering. But sound parts of aluminum alloy were not fabricated by this method because the sintering performs in the atmosphere of nitrogen gas. Yu *et al*. [4] reported the infiltration condition of aluminum alloy parts. Taminger *et al*. [5] and Mahale *et al*. [6] investigated the fabrication conditions of dense aluminum parts by electron beam melting and fabricated 2024 and 7075 aluminum alloy sample parts. The research on the fabrication of aluminum alloy parts using direct selective laser melting or laser sintering, however, has not been reported.

In this study, a laser sintering/melting machine was designed and constructed to produce aluminum alloy parts. The fabrication conditions of aluminum alloys were investigated using the constructed machine. The fabrication conditions, such as laser power, scan speed, scan pitch and layer thickness, were investigated by experiments. Finally, an automatic transmission part was fabricated in the optimum condition.

Development of Laser Sintering/Melting Machine

A laser sintering/melting machine was designed and constructed to produce aluminum alloy parts. The machine consisted of a 50 W Yb-fiber laser (wave length:1090 nm, spot size: around 170μm), a galvanometer-scanner and a computer-controlled powder delivery and build system. The laser and galvanometer-scanner were computer-controlled using the STL data converted from the CAD product data. The inside of the machine is shown in Fig. 1. The powder delivery and build system has a recoater, two powder supply unit and a laser sintering unit. The system can coat a 50 μm layer of powder (minimum). The chosen atmosphere can be changed to argon gas. The performance of this machine was confirmed.

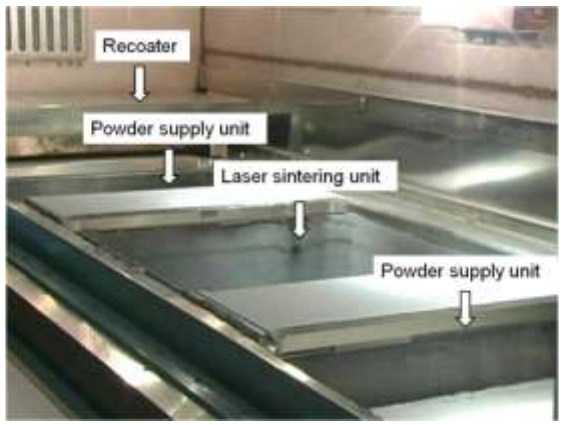


Fig.1 Laser sintering/melting machine developed in the project

Experimental Method

Powder characteristics

In this study, gas-atomized Al-12Si powder and a laser absorption material were prepared. The mean particle diameter of the Al-12Si powder was around 33μm. The Al-12Si powder had irregular shape, as shown in Fig.2. These powders were mixed using a V-blender or a ball mill. The addition of laser absorption material was 0.1~ 4 mass%.

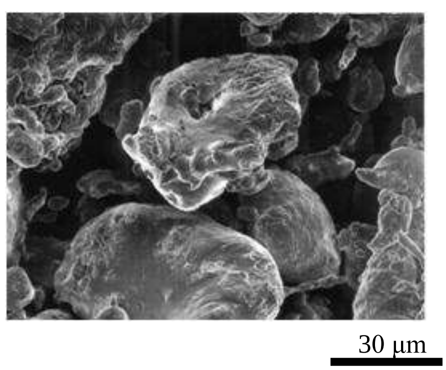


Fig.2 Shape of Al-12Si power

Experimental procedure

The mixed powders were filled into the container of the powder supply unit and then laser-scanned with the Yb-fiber laser under various fabrication conditions as follows:

- Laser power: 10~50W

- Scan-speed: 5~20 mm/s
- Scan-pitch: 0.1~0.3 mm
- Layer thickness: 0.1~0.4 mm

The surface morphology and microstructure of the laser-scanned bodies were examined by an optical microscope and a scanning electron microscope with EDX.

Results and Discussions

Fabrication conditions

(1) Effect of laser absorption material and the change in morphology of single-track with laser power and scan speed

In order to produce sound parts, it is very important to examine fabrication conditions by the constructed machine. Especially, laser power, scan-speed, scan-pitch and layer thickness are significant factors [7-10]. In this study, the optimum conditions of these factors were examined experimentally and then the single-track process map was produced.

At first, the optimum conditions of the laser power and the scan-speed were examined to obtain a smoothly continuous single-track. In the case of no laser absorption material, almost unmelted tracks or partially melted single-tracks were obtained. Thus, it was found that a smoothly continuous single-track could not be fabricated using only Al-12Si powder. Therefore, a laser absorption material was added.

Figure 3 shows the change in morphology of single-tracks with laser power and scan-speed in the case of the addition of 0.1% laser absorption material. As shown in Fig.3, in the case of 0.1% addition, a partially melted single-track was obtained in almost conditions. It was, however, found that a smoothly continuous single-track can be obtained by the addition of more than 0.5% in consideration of the relation between laser power and scan-speed. The width of single-track of aluminum alloy is fairly narrow compared to that of other metals such as alloy steels and is close to the laser spot diameter. This may be because only the laser-scanned part was melted due to high thermal conductivity of aluminum alloy. As an example of a smoothly continuous single-track, the process map of the addition of 2.0% is shown in Fig.4. Here, the shape of a single-track is roughly classified into three types as follows:

(a) a smoothly continuous track
(b) a melted and balled continuous track
(c) a partially melted track

Figure 4 also shows the change in morphology of single-tracks with laser power and scan speed in the case of the addition of 2.0% laser absorption material. Comparing to the case of 0.1% addition, the area in which a smoothly continuous single-track can be obtained widely expands in the process map as ahown in Fig. 4(a). It is found from this process map that a smoothly continuous single-track can be obtained at a laser power of more than 30 W and at a scan-speed of less than 15 mm/s. The relation between laser power and scan-speed for smoothly continuous single-tracks changes with the addition of laser absorption material. The area in which a smoothly continuous single-track can be obtained became narrower at an addition of more than 3%.

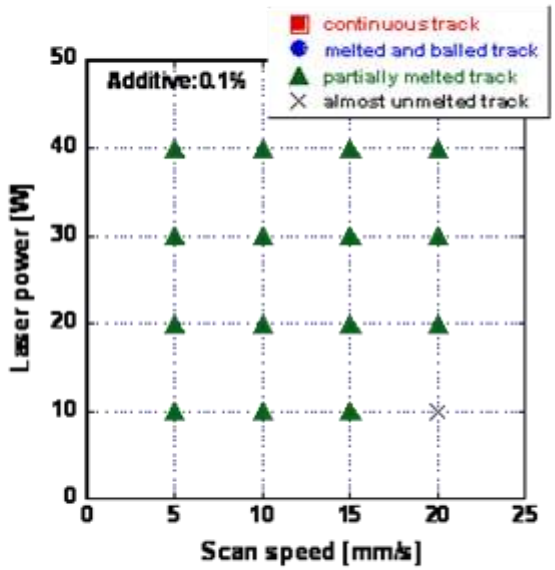
Thus, laser power and scan-speed which smoothly continuous single-tracks can be obtained are found easily by the process map.

Also, the effect of energy density, *E*, calculated by the following equation was examined.

$$E = \frac{P}{v\ d}\ [\mathrm{J/mm^2}]$$

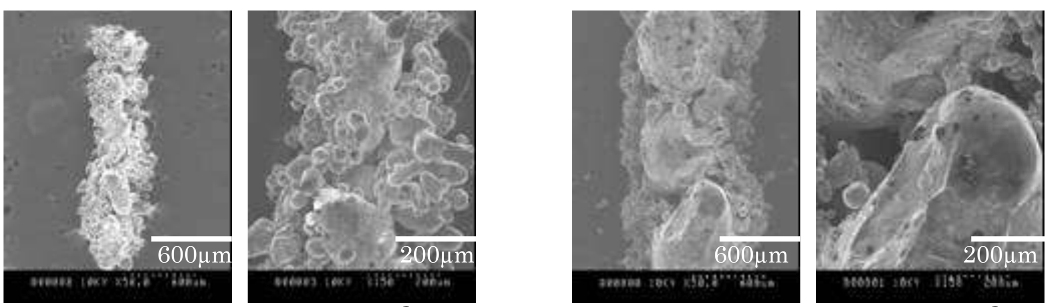
Where *P*=laser power [W], *v*=scan-speed [mm/s] and *d*=laser spot size [mm].
The values calculated as 0.17 mm in laser spot size are shown in Fig.4(a). It is found from this

figure that it is difficult to obtain a smoothly continuous single-track at an energy density of less than approximately 10 J/mm^2.



(a) Relation between laser power and scan speed

▲ partially melted track



(10 W, 10 mm/s, 5.9 J/mm^2) (40 W, 10 mm/s, 22.5 J/mm^2)

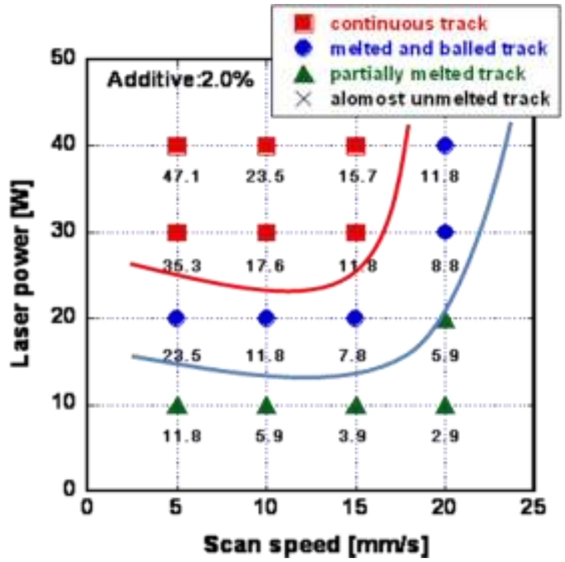
(b) Change in shape of single-scan tracks with scan speed

Fig.3 Change in morphology of single-track with laser power and scan speed (0.1% laser absorption material)

(2) Fabrication conditions of the surface

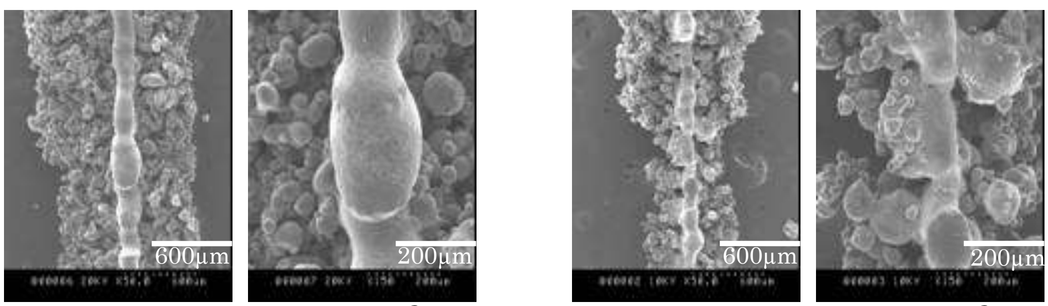
The change in surface state of the laser-scanned body with scan-pitch was examined. The scan-pitch was examined between 0.1～0.3 mm. The scanning pattern is shown in Fig.5. The fabrication of the smooth surface was difficult with a scan-pitch of 0.2 mm and 0.3 mm because the laser spot size is around 0.17 mm. As mentioned above, this is because the width of single-track of aluminum alloy is close to the diameter of laser spot. As a result, it was found that the optimum scan-pitch is between 0.1mm and 0.13 mm. This value is approximately 1/3 overlap of the width of track which is similar to that of other metals.

The laser-scanned surface state is affected not only by scan-pitch but also addition of laser absorption material, laser power and scan-speed. In the case of the addition of 4.0% laser absorption material, the laser-scanned body was cracked due to large shrinkage. Therefore, the addition content of laser absorption material was set at 2%.



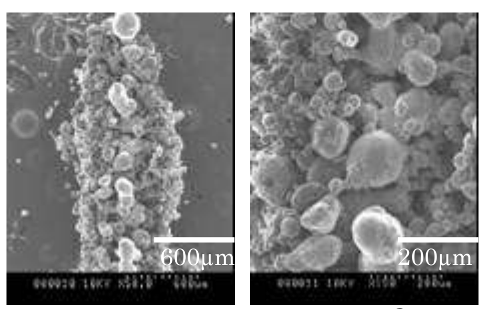
(a) Relation between laser power and scan speed

■ Continuous track ● melted and balled track



(40W, 5mm/s, 47.1 J/mm^2) (20W, 5mm/s, 23.5 J/mm^2)

▲ partially melted track



(10W, 10mm/s, 5.9 J/mm^2)

(b) Change in shape of single-scan tracks with scan speed

Fig.4 Change in morphology of single-track with laser power and scan speed (2.0% laser absorption material)

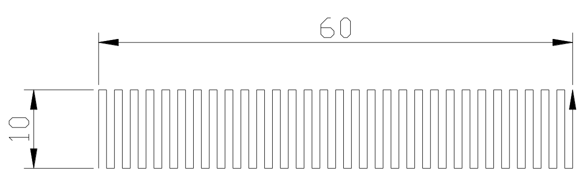
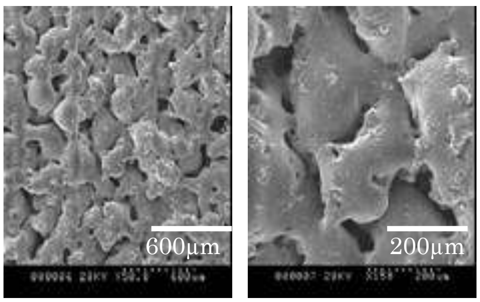


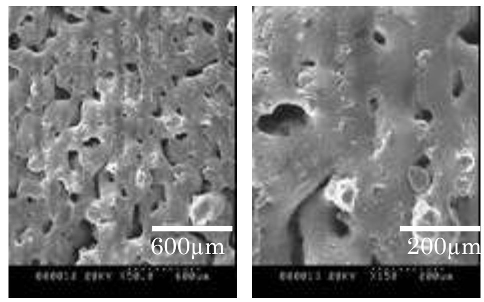
Fig.5 Laser scanning pattern (mm)

Figure 6 shows the change in the surface state of the laser-scanned body with laser power at a scan-speed of 20 mm/s and at a scan-pitch of 0.116 mm. As shown in this figure, the smooth surface of the laser-scanned body can be fabricated at a laser power between 30 W and 50 W. The surface of the body laser-scanned at 40 W is most smooth with fewer pores. Figure 7 shows the change in the surface state of the body laser-scanned with a scan pitch at a laser power of 40 W and at a scan-pitch of 0.1 or 0.116 mm. As shown in this figure, the smooth surface of the laser-scanned body can be fabricated at a scan-speed between 15 and 25 mm/s.

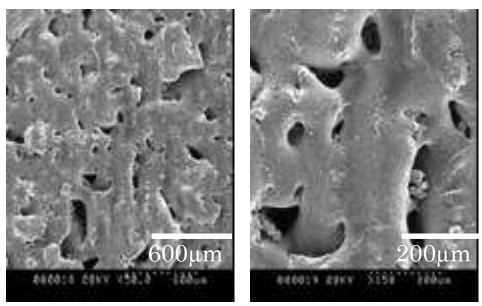
As a result, it was found that the smooth surface of the laser-scanned body can be fabricated at a laser power between 30 W and 50 W, at a scan-speed between 15 mm/s and 25 mm/s and at a scan-pitch between 0.1 mm and 0.13 mm.



(a) 30 W



(b) 40 W



(c) 50 W

Fig.6 Change in surface state of the laser-melted body with laser power
(laser absorption material:2%, scan-speed:20 mm/s, scan-pitch:0.116 m)

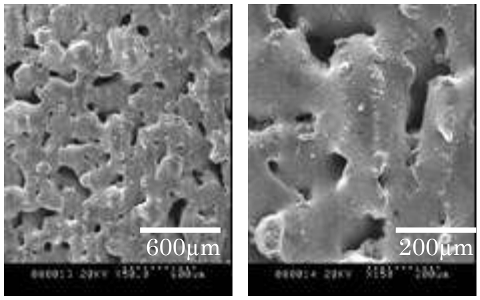
Aluminum alloy prototype production

(1) Effect of layer thickness

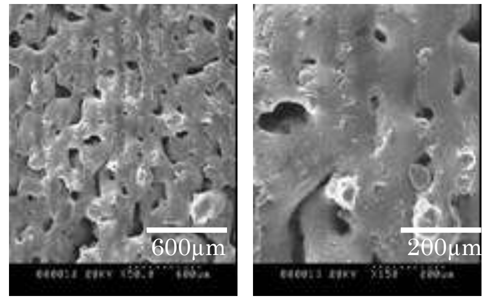
It is important to examine the effect of layer thickness to fabricate a sound body. In this research, the effect of layer thickness was examined between 0.1 and 0.4 mm. In the case of test specimens, a sound body could be obtained at a layer thickness of 0.25mm. As mentioned above, the optimum fabrication conditions are as follows:

- Content of the addition: 2%
- Laser power: 40 W
- Scan-speed: 20 mm/s
- Scan-pitch: 0.116 mm
-

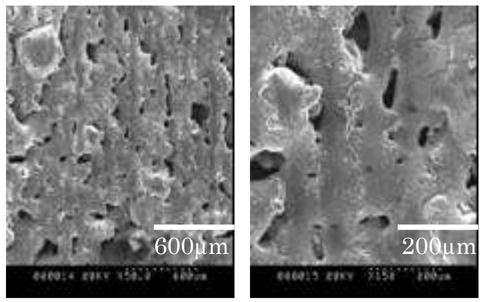
An automatic transmission part in 1/3 size was fabricated under these conditions as shown in Fig.8. As shown in Fig.8(b), delamination took place. This may be because of weakness of interlaminar strength against thermal deformation. Therefore, in order to improve the interlaminar strength, the layer thickness decreased to 0.18 mm which is nearly equal to the laser spot diameter. As a result, as shown in Fig.8(c), the layered body did not delaminate, but cracked.



(a) 15 mm/s

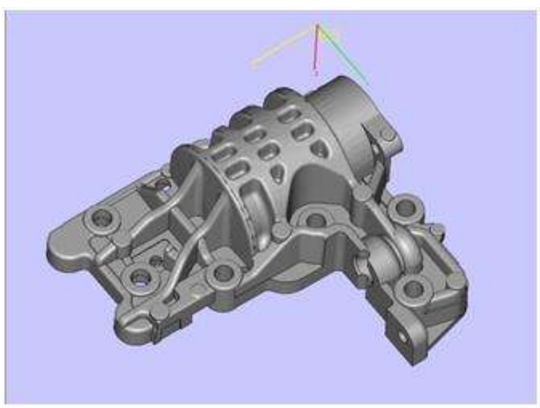


(b) 20 mm/s



(c) 25 mm/s

Fig.7 Change in surface state of laser-sintered body with scan speed
(laser power:40 W, scan-pitch:0.1 or 0.116 mm)



(a) CAD data

(b) Layer thickness 0.25 mm

(c) Layer thickness 0.18 mm

(d) Layer thickness 0.18 mm
(two times scanning)

Fig.8 An aluminum alloy prototype of automatic transmission part

(2) Effect of laser annealing

As mentioned above, cracks occurred with increasing thickness of the layered body even in the body fabricated in the optimum condition. Therefore, laser annealing was performed after first laser scanning. As shown in Fig.8(d), an aluminum alloy product without crack could be fabricated by applying laser annealing. Thus, it was found that laser annealing is so effective to fabricate a sound body of aluminum alloy prototype.

Conclusions

In this study, a direct selective laser sintering/melting machine was designed and constructed to produce aluminum alloy parts.

(1) The performance of the designed and constructed machine was confirmed.

(2) It was found that a smoothly continuous single-track can be obtained by the addition of more than 0.5% of absorption material.

(3) Laser power and scan-speed with smooth continuous single-tracks can be obtained when using the process map.

(4) It was found that the smooth surface of the laser-scanned body can be fabricated at a laser power between 30 W and 50 W, at a scan-speed between 15 mm/s and 25 mm/s and at a scan-pitch between 0.1 mm and 0.13 mm.

(5) It was found that choice of layer thickness which is nearly equal to the laser spot diameter and the application of laser annealing are effective to fabricate a sound layered body of aluminum alloy.

Thus, an aluminum alloy prototype was successfully produced using optimum laser scanning conditions.

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Imanishi Manufacturing Co., Ltd (Project sub-leader: Toshifumi Imanishi)
Castem Co., Ltd (Leader: Hideki Nakayama)
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Aspect Inc. (Leader: Masashi Hagiwara)

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