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Flexible manufacturing of metallic products by selective laser melting of powder

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Abstract

In order to produce metallic parts directly from powder material using CAD data, the selective laser melting (SLM) process has been developed. From a series of material tests, nickel-based alloy, Fe alloy and pure titanium powders are found to be feasible for fabrication of metallic models by SLM. Finite element simulation shows stress distribution within the solid single layer formed on the powder bed during forming and some methods for avoiding defects in the products are suggested. The die for metal forming from the nickel-based alloy and the pure titanium models of bone and dental crown are demonstrated. The density of the model made by SLM is higher than 90% of the solid model. The mechanical properties of the formed model can be improved to those of the solid by post-processing.

Keywords: Rapid prototyping; Selective laser melting; Metallic model; FEM analysis; Mechanical property

1. Introduction

Global competition forces the industries to improve manufacturing processes and to speed up the product development cycle. One of the promising technologies to meet the demands for reduction of time and cost in manufacturing is rapid prototyping (RP), in which physical models can be fabricated directly from CAD data in a layer-by-layer additive manner. Many RP technologies based on layer lamination have been developed in the last decade [1,2], and the models of plastics are used as prototypes of new products, master models of investment casting and physical models for surgical procedures. To realize rapid tooling and rapid manufacturing, development of processes for metallic models is desired.

In order to produce strong metallic models directly from metallic powders by RP, the selective laser melting (SLM) method has been proposed [3–5]. Metallic powders of single composition are successively melted in a microscopic zone by laser energy and solidify without leaving much porosity. From a series of test on some materials, nickel-based alloy, Fe alloy and pure titanium are found to be good candidates for making three-dimensional models. In this paper, metallic models made by SLM for applications to industrial and medical areas are presented.

2. Selective laser melting (SLM)

Fig. 1 shows SLM system developed for fabrication of metallic models. A pulsed Nd:YAG laser (LUXSTAR) with a maximum average power of 50 W and a peak power of 3 kW is used to melt metallic powders. The laser beam is carried through the optical fibre, and it is focused on the powder bed. The processing with the laser beam is carried out in the chamber filled with inactive gas such as argon and nitrogen to avoid oxidation. The three-dimensional model is built on the base plate by the movement of the laser head attached to an x–y table controlled with a PC.

In SLM process, a powder layer is deposited onto the base plate attached to the piston. The laser beam scans the powder bed according to the slice data of the model, and the first solid layer is made on the base plate. Then, the piston is lowered, and the next powder layer is deposited.

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Successive scanning and lowering of the powder bed are carried out until the model is completed. Fig. 2 shows the scanning strategy of the laser for fabrication of three-dimensional models. One cycle of the scanning process is as follows: (1) scanning only outline; (2) scanning outline and hatching inside in the x direction; (3) scanning only outline; and (4) scanning outline and hatching inside in the y direction.

Table 1 shows the basic forming conditions used in the experiment of SLM. The laser irradiation conditions are the average power of 50 W, the peak power of 1 kW, the pulse duration of 1 ms and the repetition rate of 50 Hz. The spot diameter of the laser beam on the powder bed is 0.75 mm, and the hatching space is 0.75 mm and the layer thickness is 0.1 mm.

3. Materials

To find appropriate metallic powders for SLM process, single scanning test is carried out using several kinds of materials: aluminium, copper, iron, stainless steels (SUS 316L), chromium, titanium and nickel-based alloy [6]. In this test, powders are laid with a thickness of 10 mm, and the laser beam is scanned linearly only once over the powder bed in nitrogen atmosphere. The suitable powders for processing are found from the observation of the solidified parts on the powder bed.

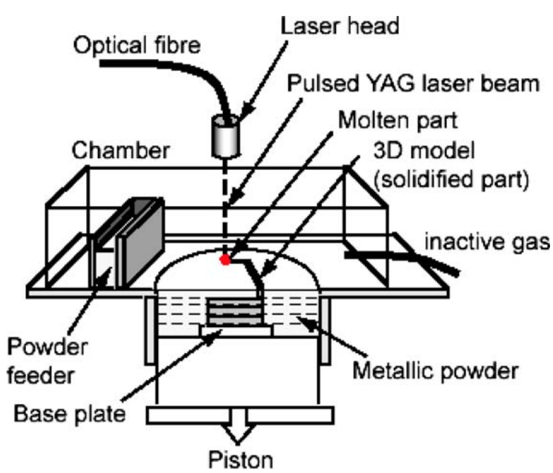


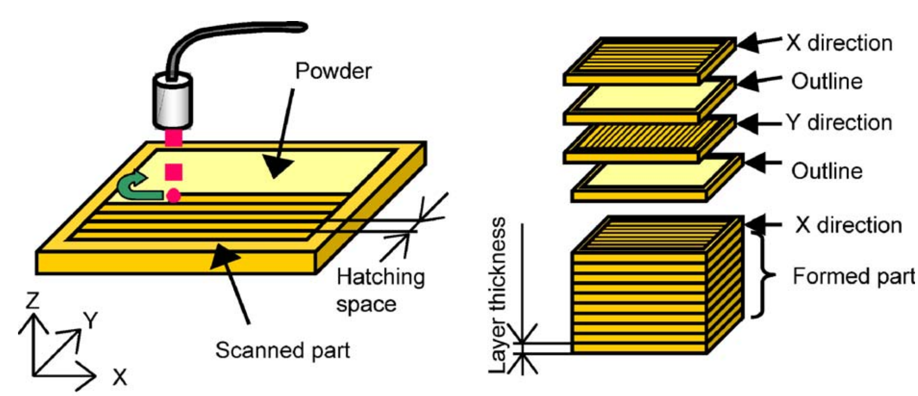
Fig. 1. Schematic illustration of selective laser melting system.

Fig. 3 shows the features of solidified metals in the single scanning test. They are classified into two types: ‘‘non-linear (ball)’’ and ‘‘linear’’ solidification. In the cases of Al and SUS 316L powders, spherical solid balls are left on the powder bed. It is considered that the balls are formed by the action of surface tension in the liquid state [7]. The phenomenon is also related to the formation of oxidized film on the solidified parts with the small amount of oxygen left in the powders, because the film may hinder the already solidified part from joining with the newly melted part.

In the case of linear solidification, some different appearances of the formed bars are observed depending on the cross-sectional shapes. When the laser beam is irradiated on Cu, Fe and Cr powders, a large groove is formed in the linearly solidified bar due to shrinkage during melting as shown in Fig. 4(a). The linearly solidified bar of nickel-based alloy, however, shows a round cross section as in Fig. 4(b). Titanium powder also forms the solid bar with a round cross section in argon atmosphere. The nickel-based alloy and pure titanium powders are considered to be preferable to forming of three-dimensional models by SLM.

Table 1
Forming conditions in SLM

Average power (W)	50
Peak power P (kW)	1
Pulse duration w (ms)	1
Repetition rate f (Hz)	50
Scan speed v (mm/s)	4–8
Hatching space (mm)	0.75



(a) (b)

Fig. 2. Scanning pattern of laser beam for making three-dimensional model. (a) Hatching in X direction and (b) hatching pattern.

4. FEM analysis

One of the serious problems in SLM process using metallic powders is thermal distortion of the model during forming, which may lead to fracture of the model. Fig. 5 shows a three-dimensional model with an overhanging made by SLM using the nickel-based alloy powder. The overhanging part is fractured during forming and thus the model cannot be completed. Since the solidified part is cooled rapidly, the model tends to be deformed and cracked due to thermal stress.

When the overhanging part is formed, it is important to make the first layer without distortion on the powder bed, because the underlying powders do not restrict the distortion. To evaluate the thermal distortion of the overhanging part during forming, a method for simulating the forming process of a single layer on the powder bed in SLM has been proposed [8]. The distribution of temperature and stress within the solid layer is calculated with the heat conduction and the elastic finite element methods [9,10]. In the simulation of the forming process of a single layer on the powder bed, the solidified part is assumed to be subjected to plane-stress deformation, and the finite element mesh is constructed on the powder surface on which the laser beam is irradiated. The development of stresses in the solidified part is simulated as shown in Fig. 6 for the case when the single layer is formed with reciprocative laser scanning.

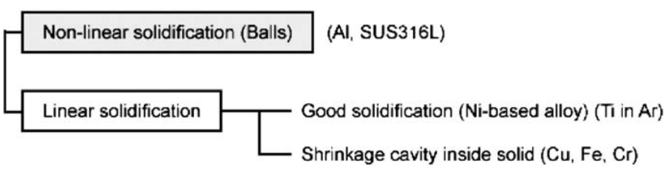


Fig. 3. Feature of solidified metal in single scanning test of several kinds of materials.

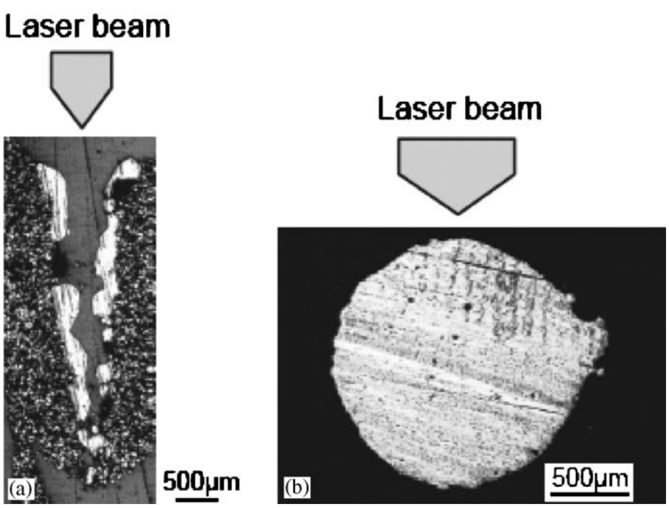


Fig. 4. Cross-sectional shape of linearly solidified bar: (a) Fe and (b) nickel-based alloy.

Fig. 7 shows the calculated distributions of stress components, σ_x and σ_y, in the solid single layer on the powder bed when the laser beam runs on the third track. A part of the solid layer is remelted during laser scanning, and the compressive stress in σ_x on the side surface of the second track is released. A stripe pattern of compressive and tensile stresses is formed in each track scanning. In the distribution of σ_y, a large tensile stress appears at the left-side end of the layer. It is considered that the large tensile stress in σ_y between the solidified tracks may cause cracking of the layer in comparison with the cracks in the experiment using the nickel-based alloy powder. As the length of scanning track increases, the amount of thermal distortion of a single layer increases and the maximum tensile stress appearing during forming becomes large. From these calculated results, it is concluded to be effective for avoiding distortion that the forming area is divided into small segments when a large layer is formed on the powder bed.

5. Metallic models

5.1. Ni and Fe alloy

An example of a three-dimensional model produced from the nickel-based alloy powder in nitrogen atmosphere

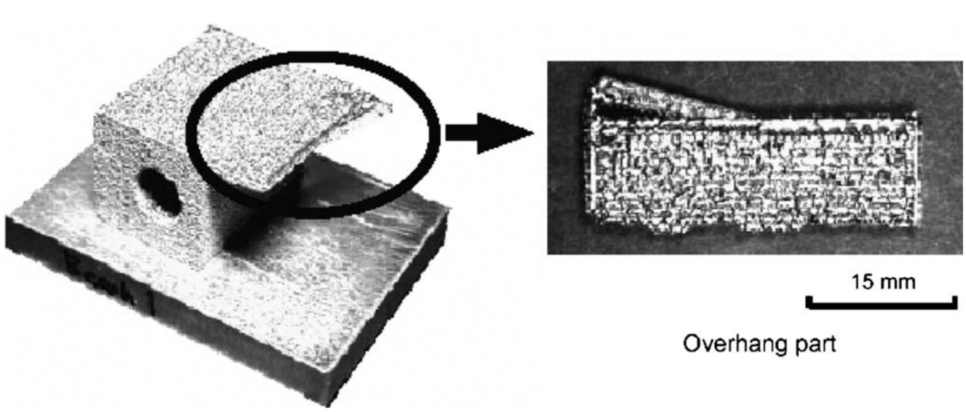


Fig. 5. Fracture of overhanging part of model during forming in SLM.

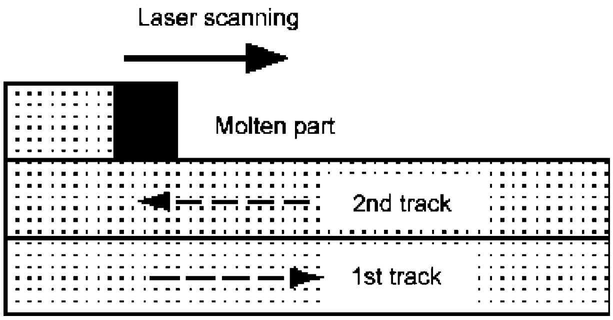


Fig. 6. Finite element simulation of single layer forming on powder bed.

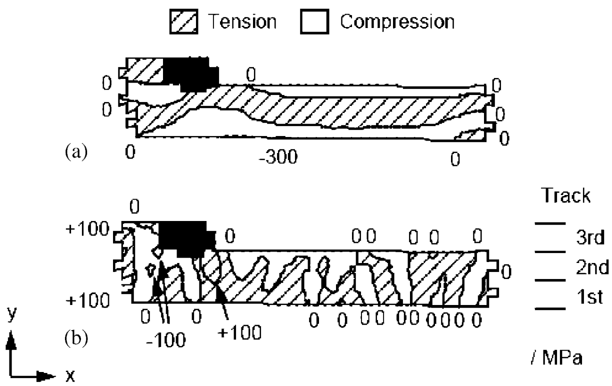


Fig. 7. Stress distribution in solid single layer during forming: (a) σ_x and (b) σ_y.

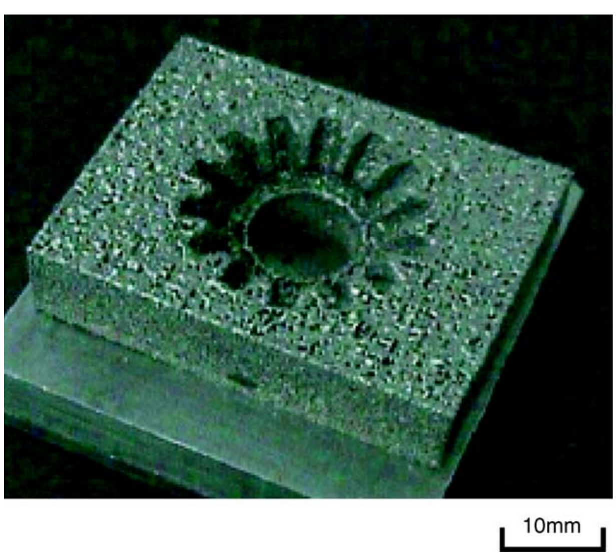


Fig. 8. Die model for bevel gear forming by nickel-based alloy powder.

is shown in Fig. 8. The chemical compositions of the nickel-based alloy powder used in the experiment are 83%Ni, 9.4%Cr, 1.8%B, 2.8%Si, 2.0%Fe and 0.4%C. The average diameter of the powder particle is about 75 μm, and the size of the model is 45 mm × 35 mm in area and 10.6 mm in height. The relative density of the model is 88% and the Vickers hardness is 740.

(1) Surface roughness and dimensional accuracy
When a model is formed by SLM, powder particles without melting stick to the solidified part and then the dimensional accuracy of the formed model does not achieve required one. To improve the dimensional accuracy and surface roughness of the formed model, a commercial machine combining RP (SLM/SLS) and high-speed milling has been developed on the basis of the fundamental research explained above [11]. The combined process is expected to enable production of moulds with complicated cooling channels for injection moulding from hard metal powders, for example chrome molybdenum steel powder, in a short delivering time.
(2) Residual stress and mechanical properties
In SLM process, a part of the model is heated rapidly and cooled during forming, which may induce residual stresses within the solid model. Residual stresses cause elastic deformation and cracks of the model in post-processing by machining and heat treatment. The fatigue strength of the model is worsened when tensile stresses remain near the model surface. For successful manufacturing of dies and moulds by SLM, it is critical to reduce the residual stresses.

To evaluate residual stresses in the model produced by SLM, a beam-shaped model is made and the residual stress is determined by measuring the change of the strain of the base plate during milling of the model in a layer-by-layer manner [12]. Fig. 9 shows the distribution of residual stress in the laminated direction. It is observed that an extremely large tensile stress remains in the top layer of the model. The residual stress decreases steeply with the distance from the top surface of the model. In the vicinity of the interface between the model and the base plate, a tensile stress exists in the model. The large tensile stress in the surface layer can be reduced by heat treatment of stress relieving at 700 °C for one hour in a furnace, and it decreases by about 70%.

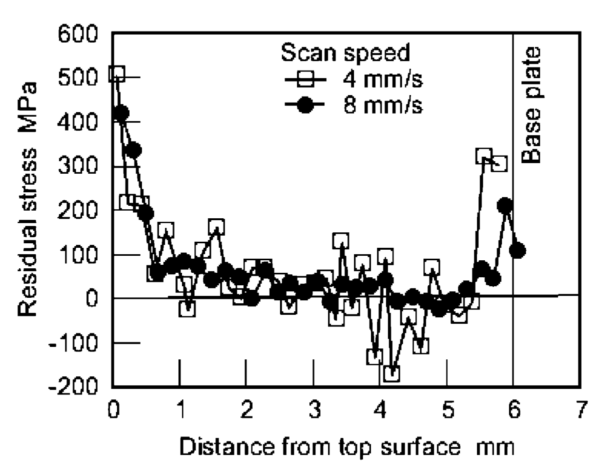


Fig. 9. Residual stress distribution within model in laminated direction obtained from steel model.

Re-scanning of laser after forming every layer is proposed to reduce the residual stresses during forming, and it decreases the tensile stress by 55%. Heating of the base plate to 160 °C during forming is also effective to reduction of the residual stress by 40%.

5.2. Titanium

Figs. 10 and 11 show the titanium models of bone and dental crown [13,14], in which the shape data of the originals were acquired using a 3D modelling machine and using the data of an X-ray CT. Commercial pure titanium powder grade 1 (TILOP 45 supplied by Sumitomo Sitix Inc.) is used in the experiment. The powder has a very low amount of hydrogen to avoid the embrittlement effect, and the particle shape is spherical. The particle diameter distribution is under 45 μm and the average particle size is 25 μm. The models for medical application are successfully formed from pure titanium powder in argon atmosphere by SLM.

The density of the titanium model made by SLM is higher than 92% of solid pure titanium. The tensile strength of the model is 290 MPa, which is similar to that of solid pure titanium grade 1: around 240 MPa. The fatigue strength of the as-formed model is low: about 10% of the tensile strength for 10^7 cycles [14].

To improve the fatigue strength of the SLM model, post-processing such as machining, heat treatment and hot isostatic pressing (HIP) is applied. Fig. 12 shows the influence of post-processing on the fatigue strength of titanium model [15]. The number of cycles before fracturing of the as-formed model marked by ■ is less than 10^6 for 35 MPa. The powder particles sticking to the model are considered to lead to crack initiation on the surface. The fatigue strength of the model with machined surface increases slightly as denoted by ○. Annealing of the machined model, ●, improves the fatigue strength. HIP makes the density of the model near 100%, and the fatigue strength (□) is very much improved.

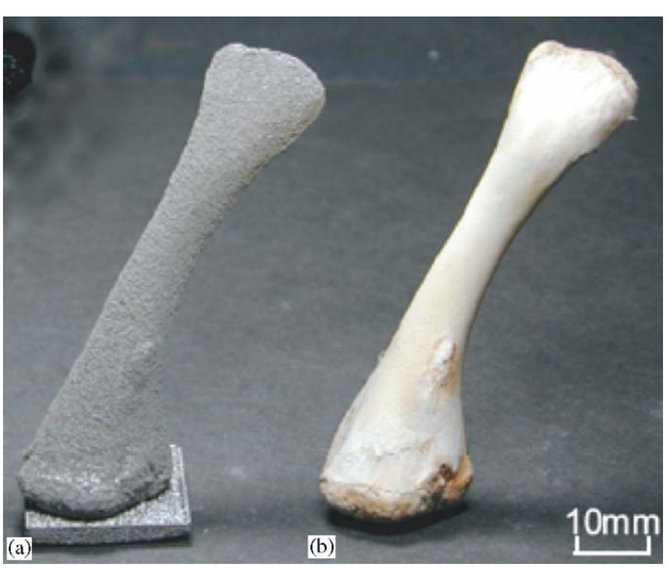


Fig. 10. (a) Titanium model and (b) original for medical application.

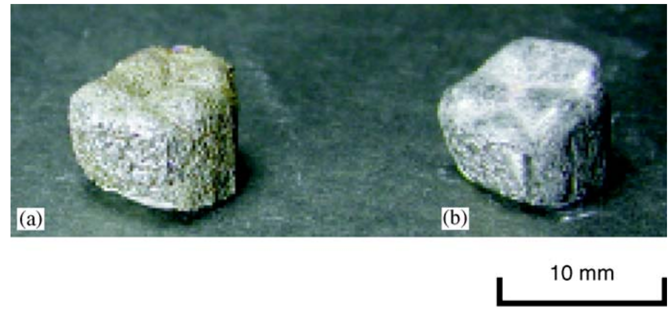


Fig. 11. (a) As-formed and (b) polished model of dental crown produced from pure titanium.

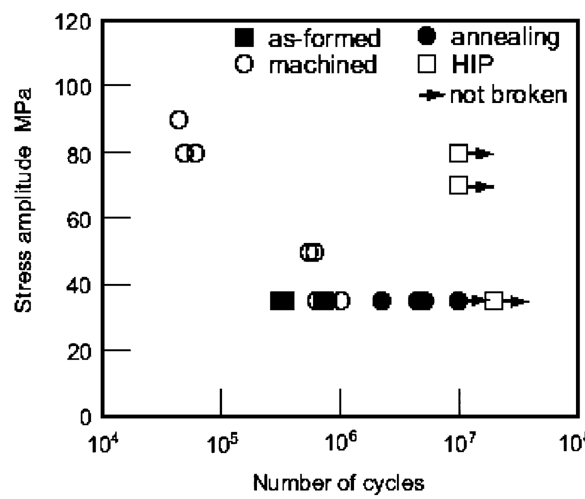


Fig. 12. Influence of post-processing, annealing and HIP, on fatigue strength of titanium model.

6. Conclusions

In order to produce the metallic parts directly from metallic powders, SLM process has been developed. The nickel-based alloy, Fe alloy and pure titanium powders were found to be good candidates for the process. The models of a die for metal forming, an artificial bone and a dental crown were demonstrated as samples made by SLM. It is expected to be applied to small lot or single production in industrial and medical areas.

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