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Microstructure-controllable laser additive manufacturing process for metal products

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Abstract

Controlling the cooling rate of alloy during solidification is the most commonly used method for varying the material microstructure. However, the cooling rate of selective laser melting (SLM) production is constrained by the optimal parameter settings for a dense product. This study proposes a method for forming metal products via the SLM process with electromagnetic vibrations. The electromagnetic vibrations change the solidification process for a given set of SLM parameters, allowing the microstructure to be varied via magnetic flux density. This proposed method can be used for creating microstructure-controllable bio-implant products with complex shapes.

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Keywords: Additive manufacturing; selective laser melting (SLM)

1. Introduction

Many investigations have demonstrated that the microstructure of an alloy affects its mechanical properties [1, 2]. Controlling the cooling rate of an alloy during solidification is the most commonly used method for varying the microstructure in traditional manufacturing processes. The cooling rate affects the phase transformation and the

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microstructure. A high cooling rate in the solidification process generally leads to a finer grain and a stiffer material [3]. The direction and growth rate of grain is influenced by crystallographic effects and heat conduction. [4].

Selective laser melting (SLM) is a promising metal additive manufacturing method that differs from traditional manufacturing processes [5]. In SLM, metal powders are melted to the liquid state by laser irradiation. A melting track is formed on the platform by a scanning laser. A free-form part can be manufactured by controlling the overlapping melting tracks. Because the thermal conductivity of the solid platform is greater than that of the metal powder, rapid heating and cooling by laser irradiation guides the heat conduction from the melting track to the platform in the SLM process [6]. Grain growth orientation and grain size in the microstructure are affected by the cooling rate and heat conduction of solidification during the SLM process. However, even though the cooling rate can be controlled via the scanning speed of the laser, an excessive scanning speed leads to discontinuous melting tracks and the formation of pores [7]. To form parts whose densities exceed 99% using the SLM process, the parameters are restricted to a small range. Moreover, the heat-affected zone around the melting pool and the heat accumulation in the SLM process also affect the formation of the microstructure [8].

Ti-6Al-4V alloy is one of the most widely used alloys in SLM due to its high specific strength and excellent biocompatibility. Custom-made metal orthopedic replacements are suitable targets for metal additive manufacturing. The required mechanical properties of bio-implants vary with contact location. Hip replacement is required with high durability at the femoral head, and high toughness at femoral stem. A lot of research effort has thus been focused on the influence of process parameters and element addition on the microstructure and related mechanical properties of titanium parts produced by SLM [9]. However, there is no suitable method for controlling the mechanical properties at different positions of an SLM product.

Some studies have reported that alloy formation can be affected by electromagnetic vibrations [10]. The grains can be refined to produce a uniform microstructure using an electromagnetic casting process. This mechanism may be useful for metal additive manufacturing. The present study proposes a method for forming various microstructures of Ti-6Al-4V via the SLM process with electromagnetic vibrations. The grain size variation was measured using X-ray diffraction (XRD).

2. Experimental setup

The experimental apparatus was made at the ITRI Southern Region Campus, Taiwan. It is a basic SLM experimental platform with a dual-magnetic-pole AC electromagnet that can deliver a magnetic flux density of up to 0.6 T at the center of the gap between the magnetic poles. The motion of the electromagnet can be controlled. The laser is directed at the gap between the magnetic poles to melt the alloy powder on the platform. The solidification of the alloy is controlled by varying the input voltage to adjust the alternating magnetic flux density.

Ti-6Al-4V powder purchased from *EOS* was produced via a gas atomization process. The parameters of the SLM process were: 175 W laser power, 500 mm/s scanning speed, and 30 μm per layer thickness in an argon atmosphere.

The crystalline structures were analyzed by XRD (MINIFLEX 2, *Rigaku*, Japan) with Cu radiation (wavelength: 1.54184 Å).

3. Result and discussion

Figure 1 (a) shows the vibrating electromagnetic force added during the SLM process by a specially made AC electromagnet. It is assumed that the area of the melting track is subjected to a similar vibrating electromagnetic force because the width of the melting track is only about 150 μm. The specially made AC electromagnet is moved in steps during the SLM process to ensure uniform force application over the overlapping melting tracks. The movement velocity can be adjusted depending on the scanning distance of the melting track produced via computer-aided design/manufacturing (CAD/CAM). A uniform vibrating electromagnetic force is applied during solidification in the SLM process. The vibrating electromagnetic force is expected to induce electric currents and disturb the grain growth of metal solidification. With restricted grain growth, the grain size can be refined.

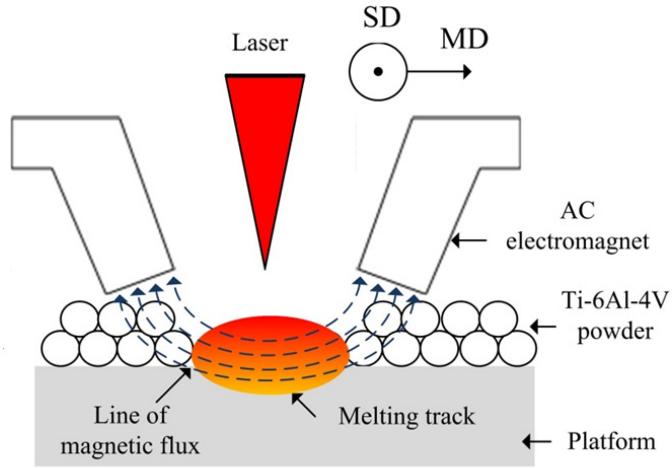

Fig. 1. Diagram of basic SLM experimental platform with dual-magnetic-pole AC electromagnet (SD: scanning direction of laser; MD: movement direction of electromagnet).

XRD is a useful tool for analyzing the material microstructure. The phases of a material and the preferred orientation can be determined from XRD patterns. The average grain size of samples was calculated using the Scherrer equation based on XRD results. Figure 2 shows XRD patterns for the Ti-6Al-4V alloy SLM samples obtained with electromagnetic vibrations at various intensities. The XRD pattern of the Ti-6Al-4V alloy sample produced by the SLM process without electromagnetic vibration has some sharp crystal peaks corresponding to (100), (002), (101), (102), (110), (103), (112), and (201) planes. Because each layer cools down very rapidly during the SLM process, it performed martensite α' phase of Ti-6Al-4V, and the microstructure is characterized by acicular nano-plates [11]. Figure 3 shows top and cross-section view optical metallographic images of a Ti-6Al-4V SLM part. The microstructure is consistent with that reported in a previous study [11].

The width of these sharp crystal peaks significantly increased for samples treated with electromagnetic vibrations. Variations of the full width at half maximum (FWHM) of these peaks with orientation in the XRD pattern are shown in Fig. 4 (a). The effect is obvious for (100), (110), (102), (103), and (101), but not obvious for (002), (112), and (201). According to the Scherrer equation, the statistical average grain size decreases with increasing FWHM. The relationship of calculated grain size and electromagnetic flux density is shown in Fig. 4 (b). Because the microstructure of the Ti-6Al-4V SLM product is acicular, the average grain size cannot fully represent the length of the acicular plate in the microstructure, but it can indicate the trend of grain refinement. Furthermore, the relative height of the highest peak (101) in the XRD pattern significantly increased when with electromagnetic flux was increased from 0 T to 0.2 T, but then decreased when the electromagnetic flux was further increased to 0.3 T. This may be caused by the effect of the electromagnetic force, but the mechanism is still unclear.

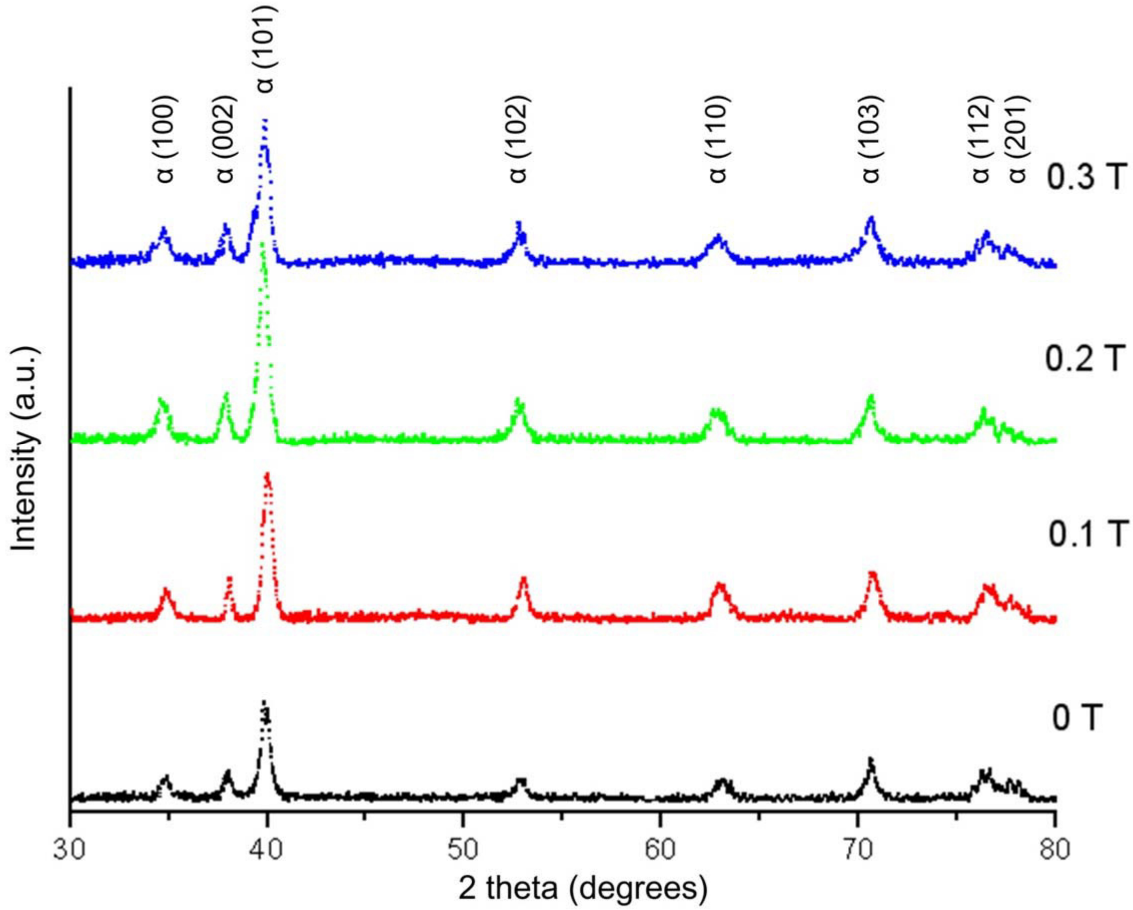

Fig. 2. XRD patterns of Ti-6Al-4V alloys cooled under various electromagnetic vibration intensities. The magnetic flux densities were 0, 0.1, 0.2, and 0.3 T.

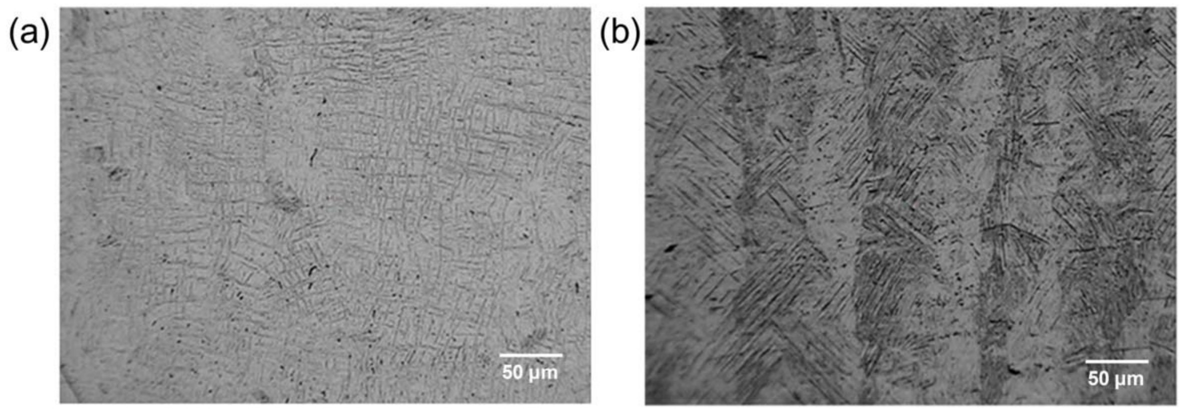

Fig. 3. (a) Top and (b) cross-section view optical metallographic images for Ti-6Al-4V SLM part. Scar bar: 50 μm.

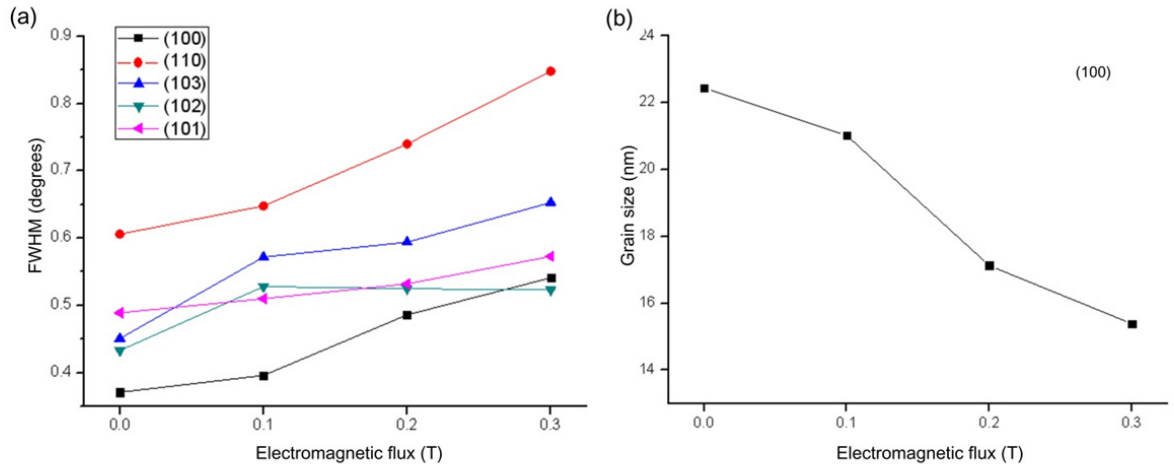

Fig. 4. Variations of (a) full width at half maximum and (b) average grain size with orientation in XRD pattern.

Figure 5 shows the proposed mechanism of the effect of the electromagnetic vibration force during solidification. The refinement by the electromagnetic vibration force for forces of up to 0.3 T is shown here, but a similar mechanism of electromagnetic casting has been shown for higher electromagnetic flux densities [10]. The metal melted in the SLM process form an induced current by the treating of electromagnetic flux, and electromagnetic field produce series effects such as electromagnetic force effect, Peltier effect, and Joule heating effect in solidification process. The electromagnetic force effect and Peltier effect disturb the original direction of grain growth, and cause supercooling condition to restrict the grain growth as the increased of electromagnetic force. Then, the grains are initially refined by the vibrating electromagnetic force. As the magnetic flux density increases, induction heating caused by Joule heating effect increases, the changed thermal gradient may counteract the supercooling condition and cause high driving force to improve grain growth and the formation of a coarse crystalline structure. The two curves of the effects of the thermal effect and grain refinement can be integrated into one curve (right side of Fig. 5) to indicate the variation of microstructure with electromagnetic force vibration. In this study, the coarse crystalline structure is not appeared under the condition of electromagnetic flux density 0.3 T.

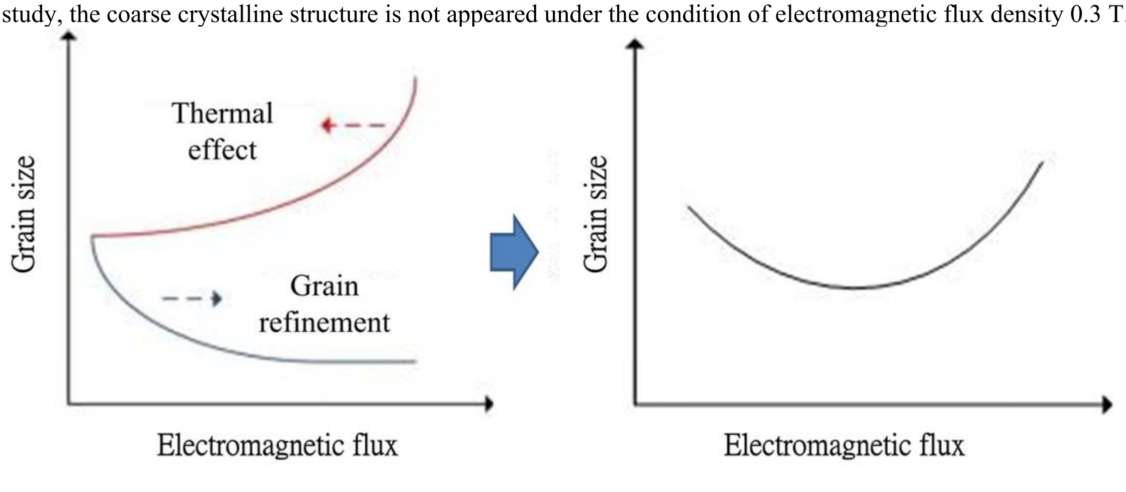

Fig. 5. Diagram of possible mechanism of effect of electromagnetic vibration force during solidification.

4. Discussion

According to the results, the electromagnetic vibration force is useful for Ti-6Al-4V SLM production. The electromagnetic vibration changes the solidification process for a given set of SLM parameters, allowing the grain size to be refined via magnetic flux density. But the full mechanism is still unclear.

The results are expected to be useful for metal additive manufacturing, especially for metallic glass production. This promising method can be applied to metallic glass and other nonmagnetic alloys in additive manufacturing to produce microstructure-controllable bio-implant products with complex shapes.

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