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A New Laser Scan Method for Microstructural Control in Selective Laser Melting Process

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Abstract

Background/Objectives: In selective laser melting (SLM) process, laser scan pattern is one of most important parameters to understand the evolution of microstructures in a part. Mechanical properties of a fabricated part are highly dependent on the evolution of microstructure. Recently, some researchers have tried to controlthe microstructures by using diverse methods. This paper proposes a method based on overlap laser scanning technique to control the microstructure in a part.

Methods/Statistical analysis: This paper uses an overlap laser scanning technique. To implement the laser scan pattern, two different sets of laser power and scan speed are used. Default set has laser power(95W) and scan speed (125 mm/s), respectively. For overlap scan, 4 different sets are used. The representative Vickers hardness (Hv) for 5 different sets are determined by averaging 10 times measurement. The representative values are compared for the effectiveness of proposed overlap scan method. To understand the change of Vickers hardness with the different sets, the size and shape of acicular α´ martensite and the concentration of O and N elements are observed.

Findings: From the measurements, Vickers hardness increases with the energy density for the overlap laser scan by about 18%, comparing to one without overlap laser scan. With the increase of the energy density for overlap laser scan, the refinement of the acicular α´ martensite increases. The change of the hardness shows the similar tendency with the change of the concentration of O and N elements.

Improvements/Applications: The results of this paper show the possibility of the microstructure design. It can also improve the design freedom by freely assigning the mechanical properties.

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I. Introduction

As one of promising metal additive manufacturing (AM) technologies, selective laser melting (SLM) process is widely adopted, due to the dimensional accuracy and the mechanical properties [1-3]. In the SLM process, Ti-6Al-4V is one of important metallic materials, thanks to the high specific strength and the biocompatibility [4-7]. The mechanical properties of selective laser melted Ti-6Al-4V part significantly depend on evolving microstructure such as the constituent phase, the morphology, the size and orientation of the prior β-grains, and the characteristic lengths of α′ martensite grown within the prior β-grains[8-10]. The evolution of the microstructure is very sensitive to heat transfer histories [11-13]. Among many process parameters in SLM process, there are three important process parameters such as laser power (W), scan speed (mm/s) and hatch spacing (mm) to influence thermal-physical phenomenon [14, 15]. Depending on the three process parameters, a melt pool, a liquid phase of metallic powders, has different heat distributions and cooling rate, leading to forming the different microstructure. It means that microstructures can be controlled by adjusting the process parameters. The ability of controlling the microstructures in the SLM process could improve the performance of components or functional parts [16, 17]. Many researchers have studied the evolution of the microstructure with various parameters [18-21]. From the recent literature, it can be found that diverse parameters have been used to change the microstructures to assign functionalities to volumes or surfaces of a part. Until now, however, a few of researches have performed the works, because the specific scan strategies in the commercialized SLM machine cannot be implemented. Thus, in developing the scan strategy to control the microstructure in a part, the applicability of a new scan strategy to the SLM machine should be considered.

In this regard, this paper proposes a method to selectively change microstructures within a part, based on the commercialized SLM machine. Specimens are fabricated with the proposed method and the fabricated specimens are analyzed to verify the usefulness of the proposed method by identifying the change of hardness, microstructures and the chemical composition.

II. Materials and Methods

In this paper, specimens were fabricated by SLM 250HL system with a spot size of 80 µm diameter. Working chamber is filled with argon gas and sustained with the oxygen content (<0.2%).Substrate on working platform is heated up to 200 °C to alleviate the thermal gradient. Ti-6Al-4V powders with the particle size from 20 µm to 63 µm were used. Two different sets of process parameters were used for the specimen fabrications. A default set of process parameters, including laser power (W) and scan speed (mm/s), is determined based on the values obtained from optimization experiments carried out in Singapore center for 3D Printing (SC3DP).

In addition, four additional sets of process parameters are used to selectively control microstructure. For the four additional sets, the optimization for hatch spacing (mm) was performed based on the relative density. The results measured for the relative densities are summarized in Table 1. Figure 1 shows the procedure of specimen fabrication. The fabricated specimens were polished and then were etched with Kroll's reagent (10 mL of HF, 30 mL of HNO_3 and 50 mL of water) for 4~5 seconds. To investigate the change of mechanical property with microstructures, Vickers micro-hardness tests were conducted by using a Future Tech FM-300e micro hardness testers on a load of 500g and 15sec dwell time. To obtain the microstructural characterization, scanning electron microscopy (SEM, JEOL JMS 6700F) were utilized. To identify the reason for the change of mechanical property from the chemical composition variation, the amount of oxygen and nitrogen in a specimen were measured by O/N analyzer (LECO, 763 series).

Table 1 : Relative densities with different sets of process parameters

Set	Energy density (W/mm.s^{-1})	P (W)	V (mm/s)	Hatch spacing (mm)							Note
				0.10	0.11	0.12	0.13	0.14	0.15	0.16	
C_0	E_0	95	125	0.987	0.989	0.988	0.984	0.984	0.987	0.984	Default part
C_1	$2 \cdot E_0$	195	125	0.988	0.981	0.991	0.988	0.976	0.977	0.984	Overlap part
C_2	$2 \cdot E_0$	95	63	0.990	0.991	0.989	0.988	0.989	0.967	0.985	
C_3	$1/2 \cdot E_0$	95	250	0.980	0.983	0.973	0.972	0.981	0.977	0.968	
C_4	$1/2 \cdot E_0$	48	125	0.919	0.936	0.896	0.930	0.903	0.892	0.921	

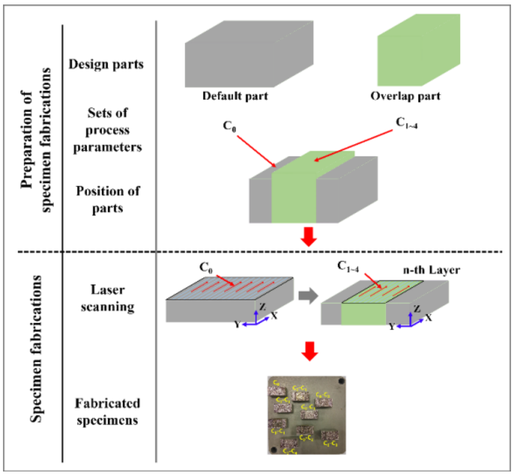

Figure1. Schematic diagram for specimen fabrication in the proposed method

III. Results and Discussion

Vickers hardness is measured to investigate the change of mechanical property in overlap area with energy densities from C_1 to C_4 cases. In each case, hardness measurements along the middle of specimens are conducted. The representative value in a position is calculated by averaging 10 measurements. For all cases, measured results are shown in Figure 2.

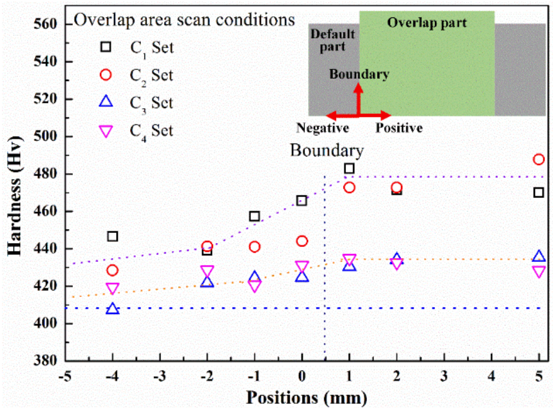

Figure 2.Variation of Vickers hardness with positions

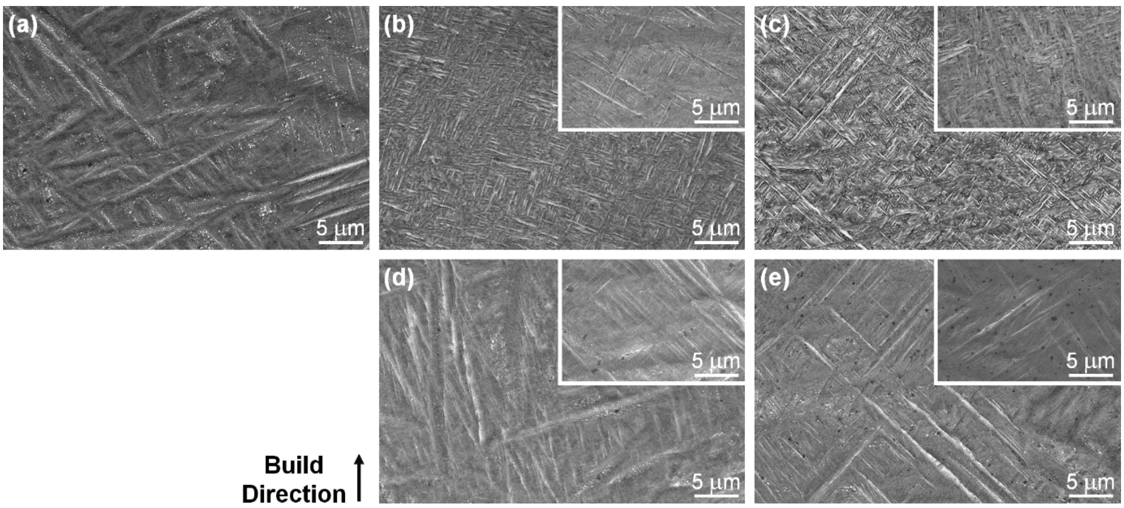

Figure3. SEM images of (a) C_0, (b) C_1, (c) C_2, (d) C_3, and (e) C_4. Non-overlap area of C_1~C_4 sets were inset, respectively.

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From Figure 2, two phenomena can be observed. First, it can be seen that the laser scanning for overlap area (hereafter, called “overlap laser scanning”) causes the increase of hardness. In the center of specimens, hardness is increased by about 70~80 Hv in C_1 and C_2 cases, and by about 20~30 Hv in C_3 and C_4 cases, comparing to hardness in C_0 set (401 Hv). The change of the hardness can be explained by investigating the refinement of the acicular α′ martensite caused by the heat transferred from the overlap laser scanning [18, 22]. Figure 3 shows the refining effect increases with the increase of the energy density for the overlap laser scanning, and proves that the refinement of the acicular α′ martensite can affect the change of the hardness. However, there are no significant differences in cases with the same energy densities (C_1 and C_2, or C_3 and C_4). It means that the increase of the hardness is only dependent on the energy density. In addition, the refinement effect by only thermal heat treatment was reported in the previous studies on the mechanical property and microstructure of conventional Ti-6Al-4V alloy (23-25). Second, hardness is gradually decreased along positions from positive to negative in all cases with overlapped area. The degree of the decrease of the hardness is dependent on the energy density for the overlap laser scanning. In C_1 and C_2 cases, hardness in non-overlap area is still higher than one in C_0 case. However, in C_3 and C_4 cases, hardness in the edge of the default area is comparable with hardness measured in C_0 case. It means that the reheating caused by the overlap scanning affects the formation of the microstructures outside of the overlap area, and the range of the reheating effect depends on the energy density for the overlap laser scanning. The insets of Figure 3 prove that the reheating effect leads to refine the acicular α′ martensite in cases with overlap area, and the degree of the reheating effect is changed with the energy density of the overlap scanning. Microstructural control including the grain size, phase, and aspect ratio is possible using the variable heating and cooling conditions with temperature, time and number of heat treatment times, then it could be affected to the mechanical properties [26, 27].

Additionally, in viewpoint of the chemical composition, oxygen and nitrogen were measured to explain the change of hardness with the energy density. The results are plotted in Figure 4. Hardness in Figure 4 is used in measured in the center of the overlap area. From Figure 4, it can be obtained that the change of the hardness is similar to the change of the amount of oxygen and nitrogen. It shows that the solid-solution hardening is the main hardening mechanism for the increase of the hardness and the degree of the solid-solution hardening is also dependent on the energy density [28].

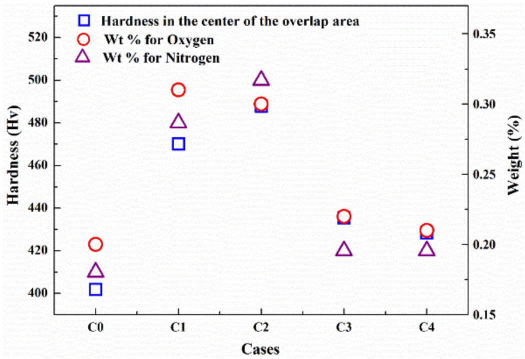

Figure 4.Comparison between hardness in the center of the overlap area and the amount of oxygen/nitrogen with the energy density of the overlap laser scanning

From the results above, it can be concluded that the overlap laser scanning can change microstructures and the amount of oxygen and nitrogen, resulting in changing hardness. It means that mechanical properties can be selectively controlled by the proposed method. The conclusions can be utilized to improve the performance of the component fabricated by SLM process. When a component is designed, engineer has used a material with homogeneous mechanical properties. However, if mechanical properties can be selectively controlled by using the proposed laser scanning method, engineer should consider a surface or a volume as a functional unit in component design, and can design a high performance component with a material [29,

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30]. Furthermore, the in-situ heat treatments by means of the overlap laser scanning could simply applied on the SLM process for the practical use, thus the study on additional effects of diverse conditions would be remained for the future works.

IV. Conclusion

This paper proposed a new laser scanning method, based on overlapping parts with different laser energy densities. In specimens fabricated with the proposed method, hardness of specimens with overlap area is higher than one of specimens without overlap area. The increase of hardness is dependent on the energy density for overlap laser scanning, and the increase is caused by the refinement of the acicular α′ martensite and the increase of the concentration of light elements such as oxygen and nitrogen.

In future work, authors will study the relationship between energy density for overlap area and the evolution of microstructure to delicately control microstructures in which engineer want to assign different mechanical property.

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