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THE POROSITY AND MECHANICAL PROPERTIES OF H13 TOOL STEEL PROCESSED BY HIGH-SPEED SELECTIVE LASER MELTING

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Abstract

Additive Manufacturing (AM) technology has the advantages of complicated geometry fabrication and integration of multiple parts. Selective Laser Melting (SLM), which is one of the AM technologies, generally takes longer manufacturing time than other manufacturing methods. In this research, the process parameters, which can achieve high-speed additive manufacturing of H13 tool steel, are investigated using a SLM machine with a 1 kW multi-mode fiber laser. As a result, the optimal process window has been determined in the process map of the laser power and the scan speed. High laser power in the process window is estimated to increase the manufacturing speed by 50 % of that with the conventional parameters. The specimen manufactured with the optimal parameters has a tensile strength of 1500 MPa, which is equivalent to the bulk samples.

Keywords: Selective Laser Melting; process parameters; H13 tool steel; mechanical properties

Introduction

Additive Manufacturing (AM) technology has been attracting attention, because it allows for manufacturing of complex-shaped metallic parts, which can be hardly manufactured by conventional processing [1]. Especially, Selective Laser Melting (SLM), which is one of the AM technologies and can process various alloys, has been used in the industrial fields such as aerospace, medical and automotive. AISI H13 tool steel is commonly used in hot-working applications including die-casting dies, inserts, forging dies, extrusion dies, and so on. Molds with conforming cooling channels fabricated by the SLM can maintain a stable and uniform cooling performance to the molding parts, which achieves improvement of the product quality and reduction of the cycle time. Therefore, SLM process has gained increasing attention in the hot-work tool field [2-4].

Recent studies have shown that H13 tool steel can be generally processed by SLM. Parameters of SLM directly affect the quality of the final part. Laakso et al. [5] indicated that Design of Experiments (DoE) approach is a practical and reliable method for SLM processing optimization. In addition, local heating and cooling of the material by the SLM causes problems such as residual stress and inhomogeneous microstructure inside the part. To overcome these problems, Gu et al. [6], Kempen et al. [7], and Sander et al. [2] investigated the effect of powder bed preheating on H13 processing.

As the next step, it is necessary to improve a productivity of SLM for H13 parts. In this study, the process parameters, which can achieve high-speed manufacturing of H13 tool steel, are investigated using a SLM machine with a 1 kW multi-mode fiber laser.

Experimental conditions

The specimens have been processed in Nitrogen atmosphere on a SLM280^{HL} machine (SLM Solutions GmbH) equipped with a 1 kW multi-mode fiber laser. The specification is as follows;

- Laser: 1 kW multi-mode fiber laser (wave length: 1.07 μm)
- Scan speed: max. 15000 mm/s
- Build size: 280×280×350 mm

The gas atomized H13 powder with irregular shape was used. SEM image of the powders is shown in Fig. 1. Table 1 is the H13 powder composition (LPW Technology Ltd.). The particle size of the powder is 10 μm to 45 μm and the powder flow rate (based on ISO 4490) is 2.68 s/50 g. Thus the flowability is good. In order to determine the process map of the high-power laser, the cubic specimens with the dimension of 15×15×15 mm were fabricated under the following conditions.

- Laser power: 600 - 1000 W
- Scan speed: 100 - 260 mm/s
- Scan pitch: 0.6 - 0.75 mm
- Layer thickness: 0.1 mm
- Spot diameter: 0.28 mm
- Preheating temperature: 200 ˚C

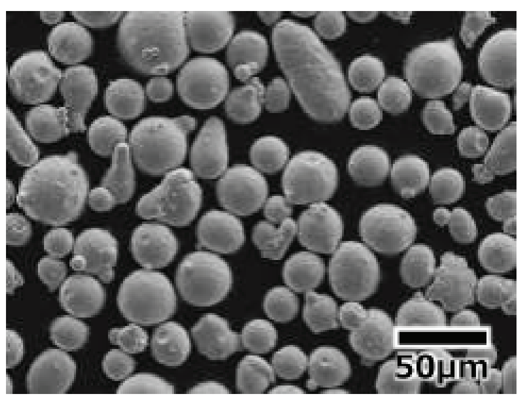

Fig. 1 SEM image of H13 tool steel powder.

Table 1 Chemical composition of H13 tool steel powder.

Chemical composition [mass%]												
C	Mn	Si	Cr	Ni	Mo	V	Cu	P	S	N	O	Fe
0.41	0.44	0.96	5.26	<0.1	1.53	1.10	<0.01	<0.015	0.004	0.04	0.02	Bal.

Basic evaluations

Process map

Optimization of the process parameters is required to avoid defects in parts. Especially, laser power, scan speed, scan pitch, and layer thickness are significant parameters for SLM. Moreover, the energy density *E* calculated from Eq. (1) is used as a significant factor [8];

$$E = P/vst \qquad (1)$$

P: laser power [W], *v*: scan speed [mm/s], *s*: scan pitch [mm], *t*: layer thickness [mm]

The process map between laser power and scanning speed was determined by relative density (Fig. 2). The density of the as-built specimens was measured by the Archimedes' principle. The density was classified into four levels as follows;

●: ≥ 99.7 %, ○: < 99.7 %, ≥ 99.4 %, △: < 99.4 %, ≥ 99 %, ×: < 99 %

The optimal process window has been determined for high relative density. This map also indicates that high density parts can be achieved even at high laser power and high scan speed. Optimal process parameters with a high-power laser are as follows;

- Laser power *P* = 600 W
- Scan speed *v* = 100 mm/s
- Scan pitch *s* = 0.7 mm
- Layer thickness *t* = 0.1 mm
- Energy density *E* = 85.7 J/mm^3

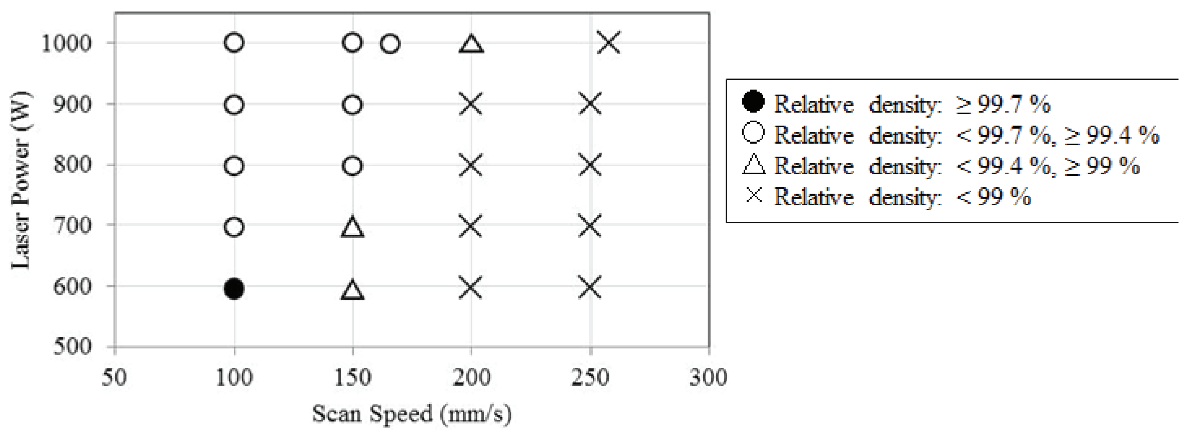

Fig. 2 Process map of H13 tool steel.

Relationship between relative density and energy density

As mentioned at previous section, the energy density significantly affects the relative density of as-built parts. Figure 3 shows the relationship between the energy density and the relative density. The relative density is higher than 99.4 % at the energy density of 85.7 J/mm^3 to 128.6 J/mm^3. In addition, the relationship with the high-power laser is revealed to be equivalent to that with a conventional laser, which is equipped on the same machine and has laser power of 400 W and spot diameter of ϕ 0.08 mm. Consequently, it is suggested that the high-power laser would improve productivity. For example, using high-power laser the scan speed can be increased, based on the equation (1) of the energy density.

In order to compare between the build speed with a conventional laser and that with the high-power laser, the fabricated volume per a unit time is calculated from Eq. (2).

$$BS = vst \times 3600/1000 \qquad (2)$$

BS: build speed [cc/h], *v*: scan speed [mm/s], *s*: scan pitch [mm], *t*: layer thickness [mm]

Figure 4 shows the relationship between build speed and relative density. In case of a relative density of 99.5 % by the high-power laser, build speed is 1.5 times as high as that with a conventional laser. In the following, the SLM with a high-power laser is defined as high-speed SLM, in contrast with normal SLM using a conventional laser.

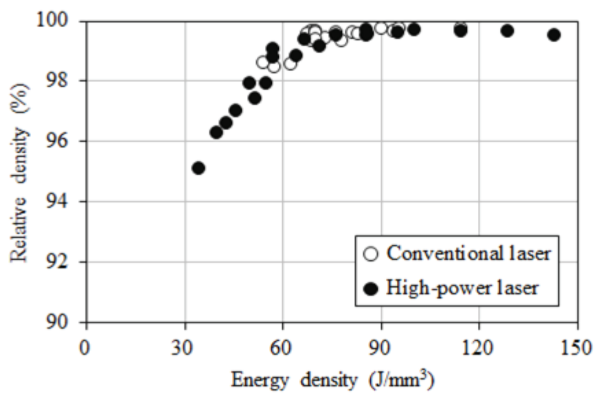

Fig. 3 The relationship between energy density and relative density.

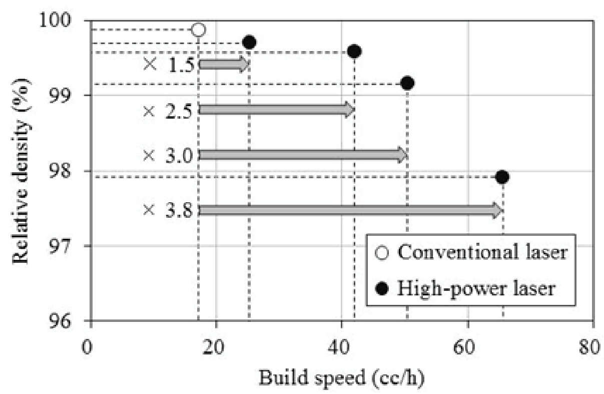

Fig. 4 The relationship between build speed and relative density.

Microstructure

The microstructure of the as-built specimen was observed using an optical microscope (OM). Figure 5 shows the OM image of specimens fabricated by normal SLM and high-speed SLM. These are cross sections parallel to the build direction of the part. As shown this figure, the melt pool size by high-speed SLM is much larger than that by normal SLM. This result may be caused by wide scan pitch and thick powder layer of high-speed SLM. This suggests that the build speed by high-speed SLM is much higher than that by normal SLM.

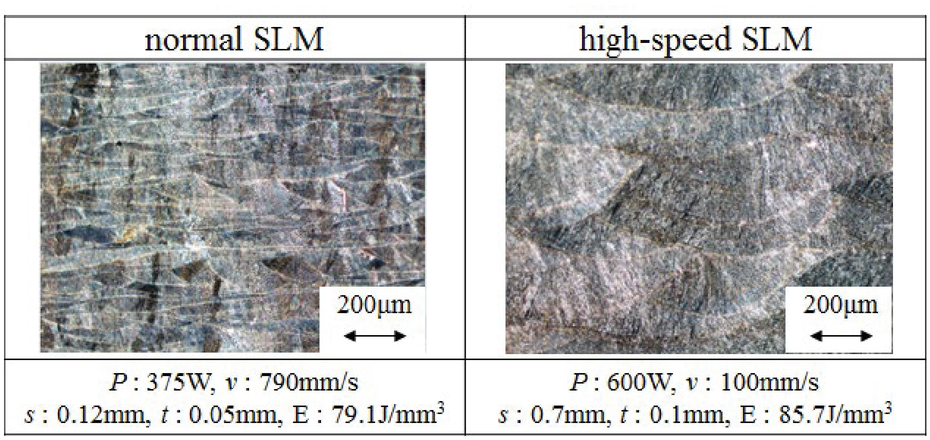

Fig. 5 OM images of the specimens.

Mechanical properties

Hardness

The hardness was measured using a micro Vickers hardness tester. Figure 6 shows the hardness of specimens manufactured by normal SLM and high-speed SLM. Hardness was measured along the direction from surface to center of specimen on the horizontal cross section. As a result, both specimens equivalently have hardness of 580 HV to 600 HV.

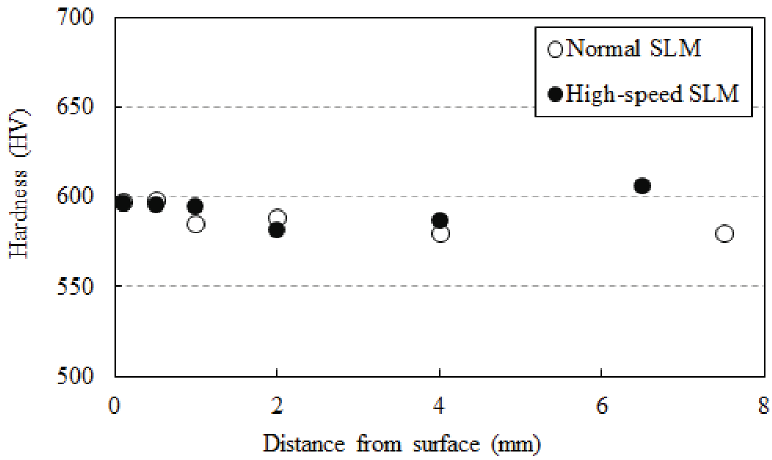

Fig. 6 Results of micro Vickers hardness measurement.

The specimens for the tensile test

To evaluate mechanical property of specimens processed with the optimum parameter, a tensile test is carried out (based on ISO 6892-1). The round rods for a tensile test were fabricated under the optimum conditions in table 2. The dimension of the specimens is ϕ 14×82 mm. Figure 7 shows the as-built specimen for tensile test. The heat treatment condition was air cooling after heating at 640 ˚C (4 h, 2 times). Figure 8 shows the specimen machined from round rods. Defects such as voids or cracks on the surface could not be observed.

Table 2 The fabricating conditions.

Process parameter		Value
Laser power	(W)	600
Scan speed	(mm/s)	100
Scan pitch	(mm)	0.7
Layer thickness	(mm)	0.1
Energy density	(J/mm^3)	85.7

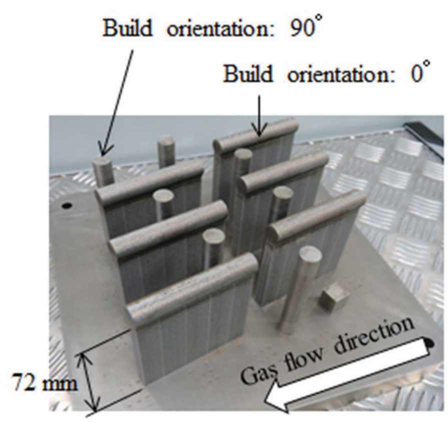

Fig. 7 The round rods for the tensile test.

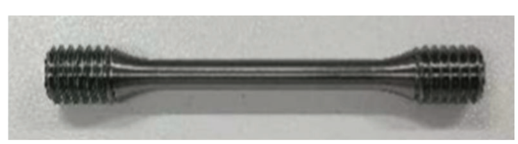

Fig. 8 The specimen of the tensile test.

Mechanical properties

Figure 9 is the result of the tensile test of the as-built specimen and the tempered specimen. The tensile strength at build orientation of 0˚ was higher than that at build orientation of 90˚. The as-built specimen and tempered specimen at the build orientation of 0˚ have tensile strengths of 1470 and 1570 MPa, respectively. The tempered specimen at the build orientation of 0˚ has lower tensile strength than the as-built one. However, it was opposite tendency at the build orientation of 90˚. This tendency is expected to be the influence of microstructure. The additional evaluation will have to be carried out in future work.

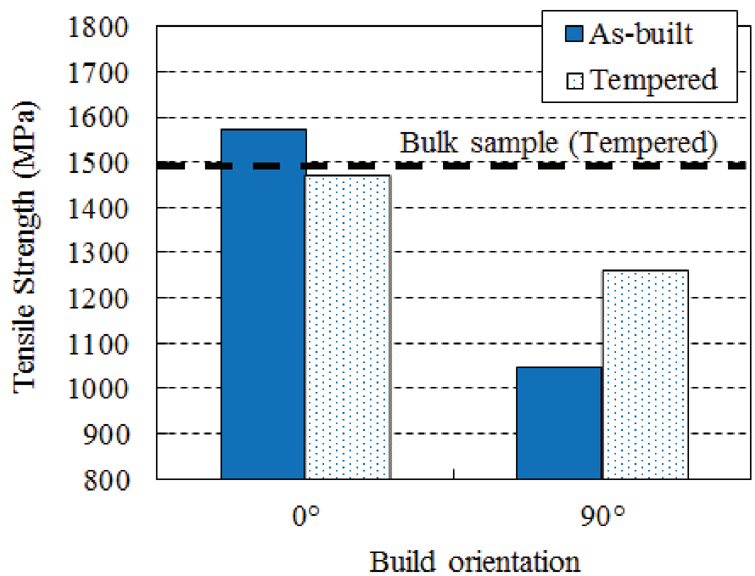

Fig. 9 Results of the tensile tests.

Conclusions

In this research, the process parameters, which can achieve high-speed additive manufacturing of H13 tool steel, are investigated using a SLM machine with a 1 kW multi-mode fiber laser. The summary is as follows;

(1) The effective process window in the process map of the laser power and the scan speed was determined by evaluating the density of the specimens.

(2) The energy density for high relative density was 87.5 J/mm^3 to 128.6 J/mm^3, which is similar to that by a conventional laser.

(3) The build speed with the high-power laser is estimated to be 1.5 times as high as that with a conventional laser to achieve relative density of 99.5 %.

(4) The tensile strength at build orientation of 0˚ was higher than that at build orientation of 90˚.

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