Solid Freeform Fabrication 2017: Proceedings of the 28th Annual International Solid Freeform Fabrication Symposium – An Additive Manufacturing Conference
Reviewed Paper

Influence of process time and geometry on part quality of low temperature laser sintering

Yuki Yamauchi*, Toshiki Niino†, and Takashi Kigure*

*Tokyo Metropolitan Industrial Technology Research Institute
†Institute of Industrial Science, the University of Tokyo

Abstract

The authors are developing a novel laser sintering process that prevents parts from warping by anchoring them to a rigid base plate. Since the powder bed temperature of the process is normally lower than in the standard process, the laser is required to supply more energy in the novel process, namely low temperature process. Accordingly, the part quality is more sensitive to laser parameters. Additionally, accumulation and dispersion of energy which is supplied by the laser through layers plays an important role in the consolidation of the powder. Thus, in low temperature process, parameter relating part geometry and time affects the part quality more than in standard high temperature process. In this research, the influence of part size and process time per layer on the density of parts as a primary index of part quality is investigated. Density decreases as the process time per layer increases. With respect to part size, density increases as parts become larger.

Introduction

Among various AM technologies, plastic laser sintering (LS) is promising for end parts production. Although LS technology has been utilized in aerospace and medical industries for more than ten years, expansion into other industries is still limited. One of the greatest drags on wide spread of the technology is material cost. There are two causes that elevate the cost. One is the high price for which we purchase powder. Normally, the price of LS powder is much higher than pellets for injection molding due to the cost of producing powder from raw material and initial development. The other cause is the large amount of powder we use in the LS process. When an LS process is finished, parts are buried in powder that remains un-consolidated. The powder is not fused intentionally but slightly fused to make a very porous cake, known as part-cake. Usually, the part-cake is separated from the parts, sieved to obtain powder form again, and reused in the next batch. Before it is used again, a certain amount of brand-new powder is added to reduce the effect of the previous process. The effect is supposed to be deterioration of polymer that is caused by preheating [1]. The maximum value in rate of used powder in feed stock that enables a successful process is defined as “recycle rate” or “recyclability.” Low recyclability directly impacts material cost of part production using laser sintering. In practical LS operation, the ratio of parts to whole bed is 5 to 10 %. On the other hand, recyclability of commercially available PA12 powder is 50 to 70 %, and the amount of the additional fresh powder is 30 to 50%. Thus, the amount of powder that we have to purchase can be ten times as much as the powder that had been consolidated to parts. It is supposed that the reduction of the deterioration improves the recyclability and reduces the cost, consequently. Additionally, it is reported that the preheat temperature is one of the dominant factors on powder deterioration [2, 3, 4].

The authors proposed a novel LS process in which part warpage is suppressed by tying parts to a rigid base plate during the process instead of high temperature preheating [5, 6]. This process allows the powder bed temperature to be lower than recrystallization temperature. In the following description, we denote the novel process as “low temperature process.” Contrarily, the normal process in which powder bed temperature is maintained above recrystallization point is denoted as "high temperature process." Although the low temperature process can provide better recyclability, as mentioned, part quality out of the process is not investigated in details.

When the bed temperature is lower, the laser is required to supply more energy than in high temperature process [7]. Accordingly, part quality is more sensitive to laser scan parameters, part geometry, and parts arrangement in low temperature process than high temperature one. The aim of this research is to reveal dominant factors that affect part quality in low temperature process. Previously, it was reported that mechanical properties is very much depending on geometry and time to process one layer in high temperature process [8, 9, 10, 11]. In this paper, we focused on process time that is required to process one layer, hereinafter referred to as *layer time*, and part geometry as parameters of accumulation and dispersion of supplied heat energy.

Material and Methods

Laser sintering apparatus

A commercially available LS machine (RaFaEl 300F, Aspect Inc.) was used. This machine is installed with a fiber laser while the typical commercially available machine uses a CO_2 laser. Since the fiber laser has a shorter wave length than the CO_2 laser, its beam is focused into a small spot more easily. Basic specifications of this machine are summarized in Tbl.1.

Tbl.1 Specifications of LS machine

System	RaFaEl 300F
Type of laser	Fiber laser (λ=1064nm)
Nominal laser spot diameter	170 μm
Maximum laser power	20.0 W
Work volume	290 mm×290 mm×370 mm

Material

PA11 powder (Aspex-FPA, Aspect Inc.) was employed. Since light from the fiber laser is not absorbed by the base resin of this powder, black pigment dedicated to improve absorption is compounded in each powder grain (Fig.1). Properties of this powder are summarized in Tbl.2. This material recrystallizes in the rage between 160 °C and 175 °C. In low temperature process, the powder bed is preheated at 140°C, which is lower than the recrystallizing range.

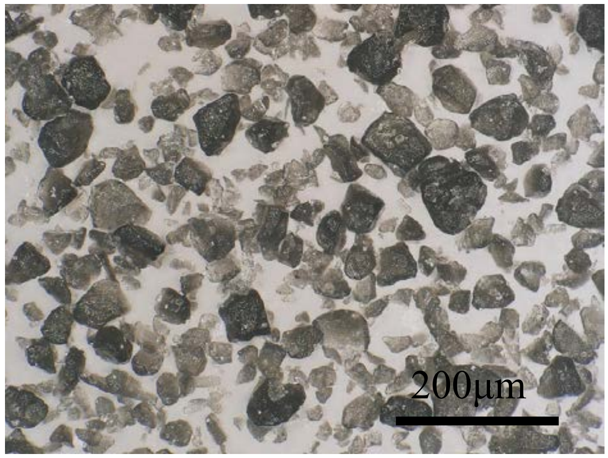

Fig.1 Optical micrograph of PA11 grains

Tbl.2 Material properties of Aspex-FPA

Type of material	PA11
Melting point	201 °C
Recrystallization temperature	167 °C
True density	1.01 g/cm^3
Average particle size	50 μm

Base Plate for low temperature process

The base plate to which parts were anchored to prevent warpage during process was prepared. It was a flat PA12 (Aspex-PA, Aspect Inc.) plate of 13mm×200mm×200mm as shown in Fig. 2. The plate was manufactured using high temperature process with a commercially available LS machine (RaFael 550, Aspect Inc.). The plate was fixed to a back-up plate with screws to ensure the flatness of the anchoring surface.

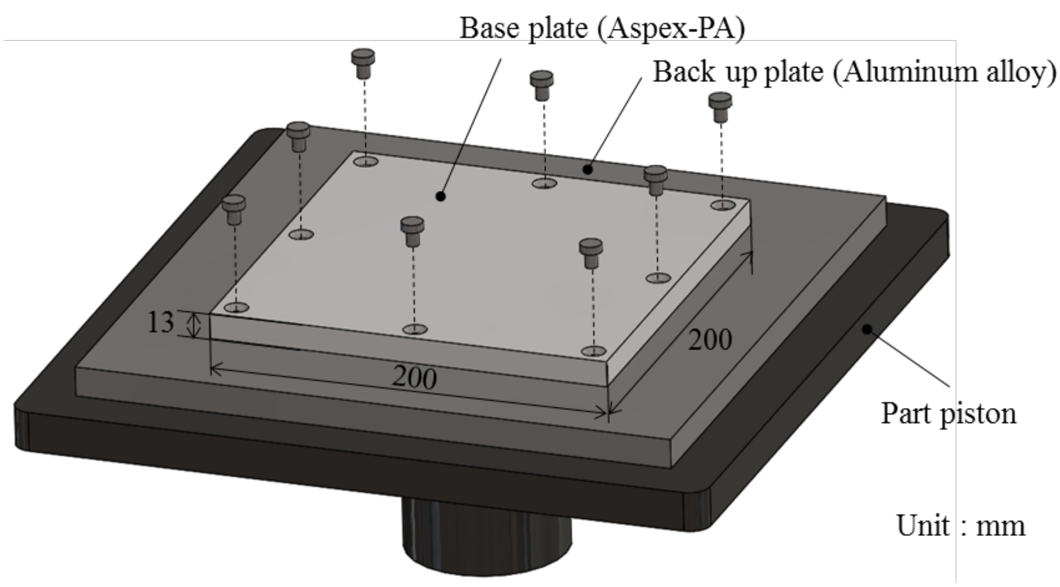

Fig.2 Schematic view of base plate

Density measurement

Density of sintered parts has a strong correlation with mechanical properties [12]. Therefore, relative density of specimen was evaluated as a part quality. Relative density ρ_r of a specimen can be obtained by

$$\rho_r = \frac{m}{v_b \times \rho_t}$$

where m, v_b and ρ_t are mass of the part, part volume and true density of the powder material. Here, ρ_t of the material employed in this research is 1.01 g/cm^3. The mass of part was measured by an electronic balance (AUX220, Shimadzu Inc.). The part volume was calculated by measuring the dimensions of each axis direction with calipers and micrometers.

Build parameters of each process

The build parameters are summarized in Tbl.3. For comparison, a specimen was also built with the high temperature process using the parameter set that is recommended by machine and material manufacturer. Parameters for low temperature process was decided so that obtained density becomes equivalent to that from high temperature process [13]. Laser was scanned in the direction of *x*-axis, and layering direction was z-axis.

Tbl.3 Build parameters

Process	Laser power	Scan speed	Scan interval	Energy per unit area	Layer thickness	Powder bed temperature
Low temperature	15W	2.0 m/s	90 μm	83 kJ/m^2	100 μm	140 °C
High temperature	10W	10.0 m/s	90 μm	11 kJ/m^2	100 μm	190 °C

Relationship between layer time and density of part

The influence of layer time on the density of the part was tested. Here, we define the layer time (t_l) as the time between two layering operations. Specimens were built in each layer time (t_l= 5s, 15s, 25s, 35s, and 45s) and the density of the obtained parts was measured. The layer time consists of powder spreading, laser scanning, and platform descending. To set the layer time to specific value, a pause is inserted in the process and the pausing time was adjusted. Specimens that were designed in 20mm×10mm×5mm were built.

The influence of the sequence of processing in a layer was investigated as well. Separated regions as shown in Fig. 3 were processed in the order indicated by the number of each region. Density of hatched parts was measured to evaluate the effect of process order.

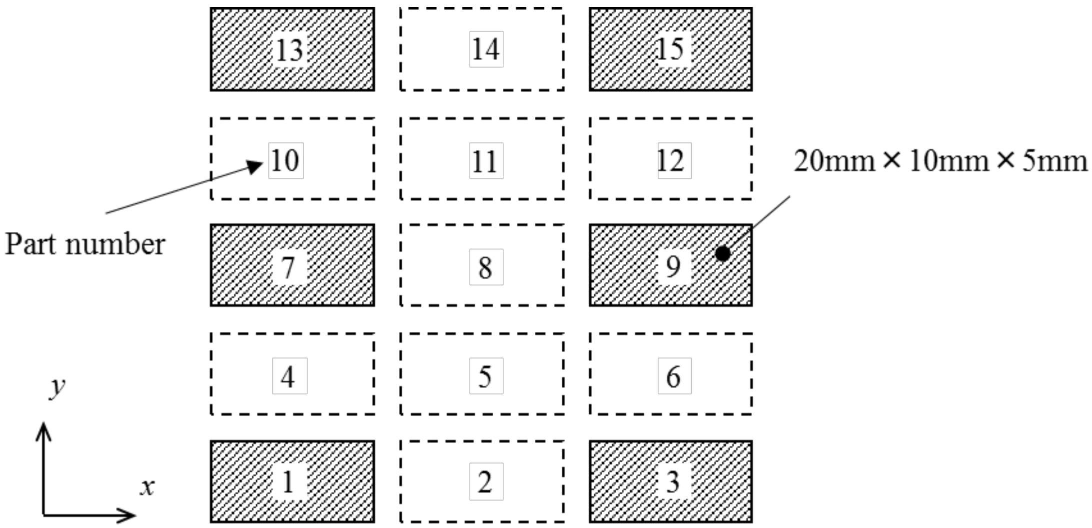

Fig.3 Arrangement of specimens and process sequence

Relationship between part geometry and density

The effect of changing size and aspect ratio of parts were investigated. Specimens that are the same in aspect ratio of cross section and different in area as shown in Fig. 4 are fabricated, and their densities were measured to evaluate how the difference in cross section area A_{xy} effects the part property.

Additionally, specimens that are the same in cross sectional area and different in aspect ratio, in contrast, as shown in Fig. 5 were tested as well.

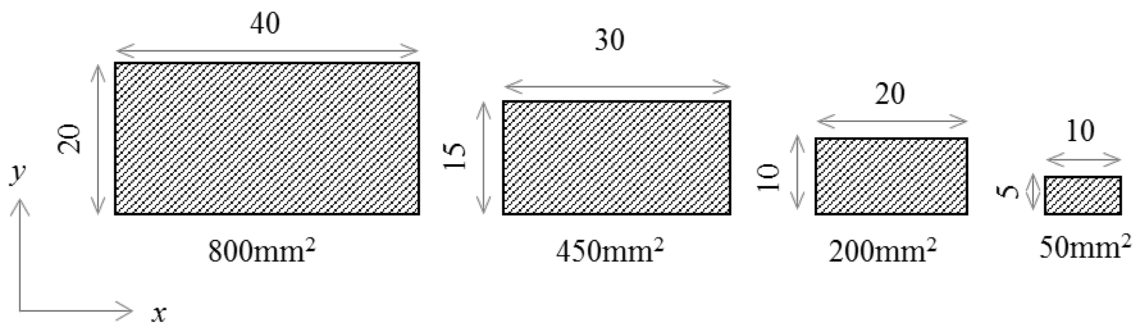

Fig.4 Cross-section area of specimens with same aspect ratio (thickness: 5mm)

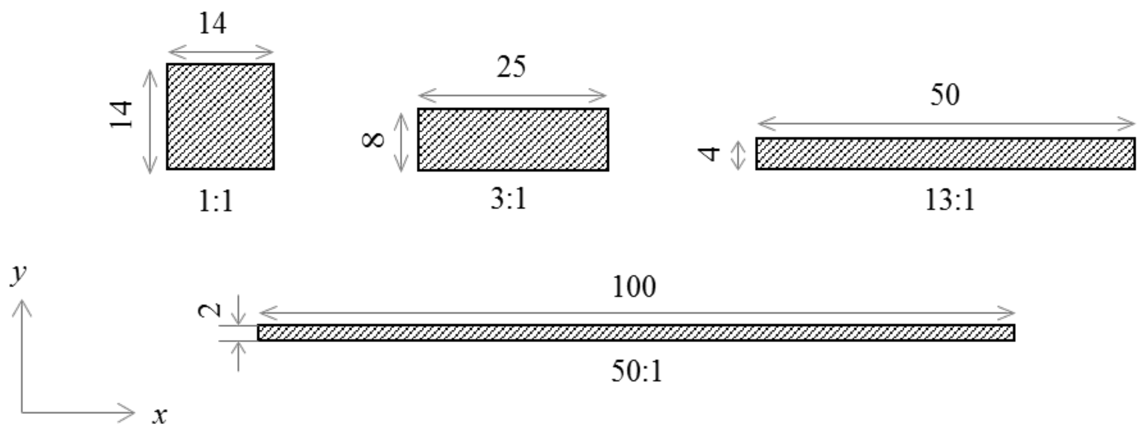

Fig.5 Aspect ratio of specimens with same cross-sectional area (thickness: 5mm)

Experimental result

Relationship between layer time and density of part

A relationship between layer time and relative density of specimens is shown in Fig.6. In the high temperature process, the variation of relative density was smaller than 3%. As a general tendency, ρ_r decreased as the layer time increased in the low temperature process. Part density decreased as layer time increased, and the decrease stopped when the layer time was more than 35s.

Relationship between order of processing in layer and relative density of specimens was shown in Fig.7. The difference in each order of processing on relative density was smaller than 2%. When the part number was bigger (that is to say order of processing was the latter), the relative density slightly decreased. When specimens shown in Fig.3 are processed, the layer time was 30s.

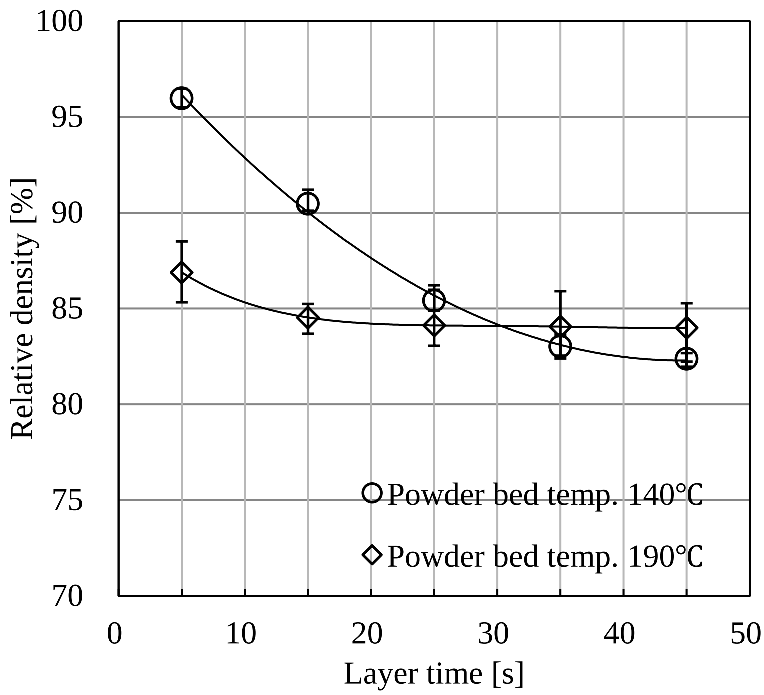

Fig.6 Relationship between layer time and relative density in each process

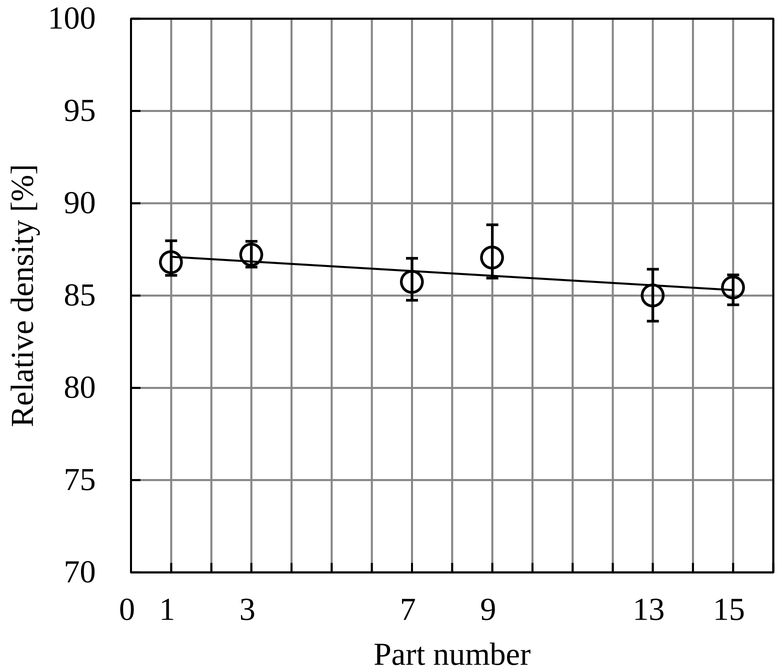

Fig.7 Relationship between order of processing in layer and relative density in the low temperature process

Relationship between part geometry and density

The relationship between the cross-sectional area of the specimens and the relative density is shown in Fig.8. In the high temperature process, when A_{xy}= 50 mm^2, 200 mm^2 and 450mm^2, ρ_r were 85%. When A_{xy}= 800mm^2, ρ_r was slightly decreased.

On the other hand, as a general tendency, ρ_r increased as A_{xy} increased in low temperature process. When A_{xy}= 50 mm^2, ρ_r was 76%. And when A_{xy}= 800 mm^2, ρ_r was 82%.

The relationship between the aspect ratio of specimen and the relative density is shown in Fig.9. In low temperature process, ρ_r decreased as the aspect ratio increased. The relative density at a ratio of 50 is smaller than at a ratio of 1 by 5%.

Fig.10 shows an X-ray CT image of horizontal cross-sections of specimens which were obtained by low temperature process. Brightness shows local density. The black (darker) region is air or a pore, and gray region is plastic. In the low temperature process, the density was uniform all over the section. Fig.11 shows a CT image of high temperature processed parts. Specimens out of high temperature process were relatively porous in the middle and dense at both ends in *x* direction or scanning direction. The width of the denser region was roughly 1 mm.

Layer times for low and high temperature process in this experiment were 54s and 26s, respectively.

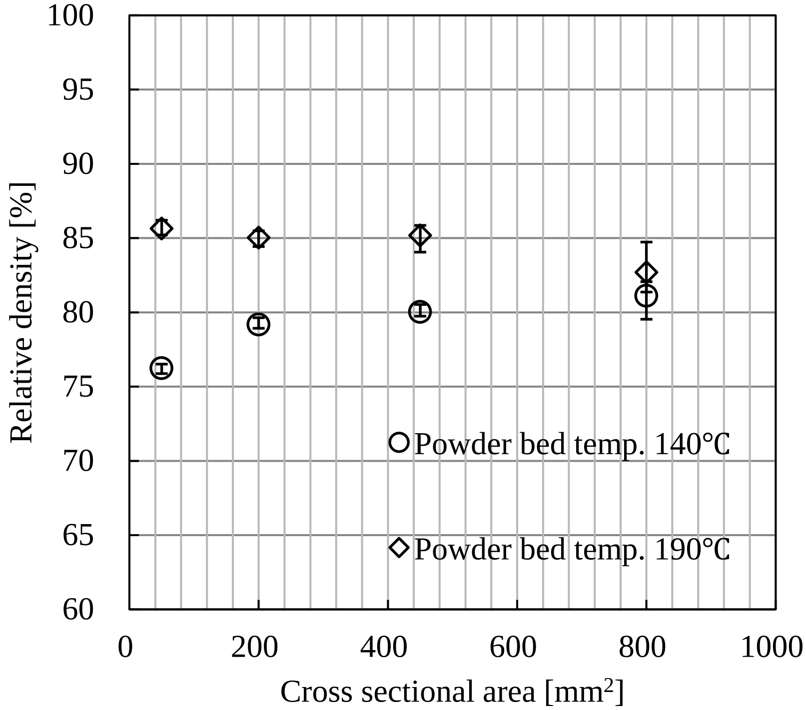

Fig.8 Relationship between cross-sectional area of rectangular specimens with the same aspect ratio and their relative density

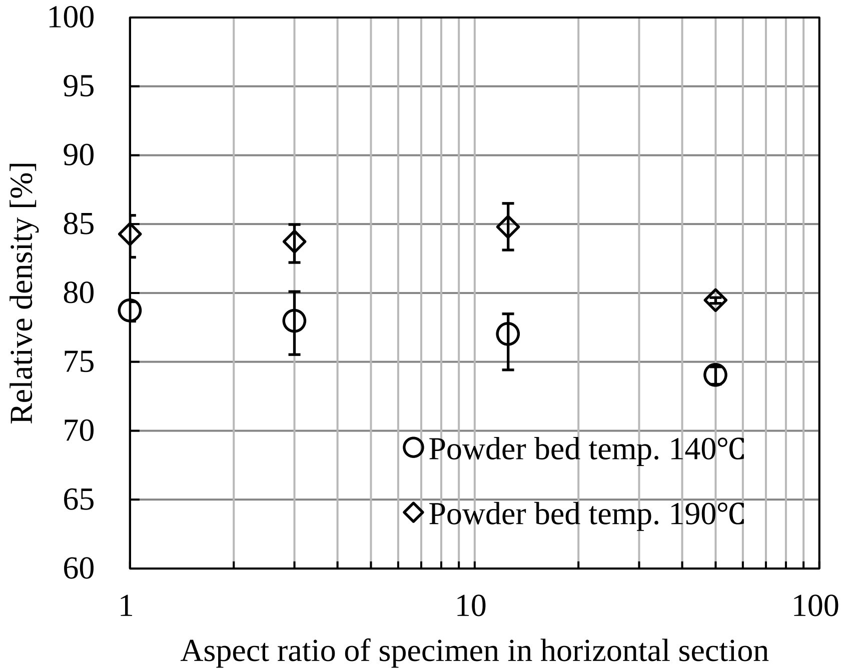

Fig.9 Relationship between aspect ratio in horizontal cross-section of specimens with A_{xy}= 200 mm^2 and relative density

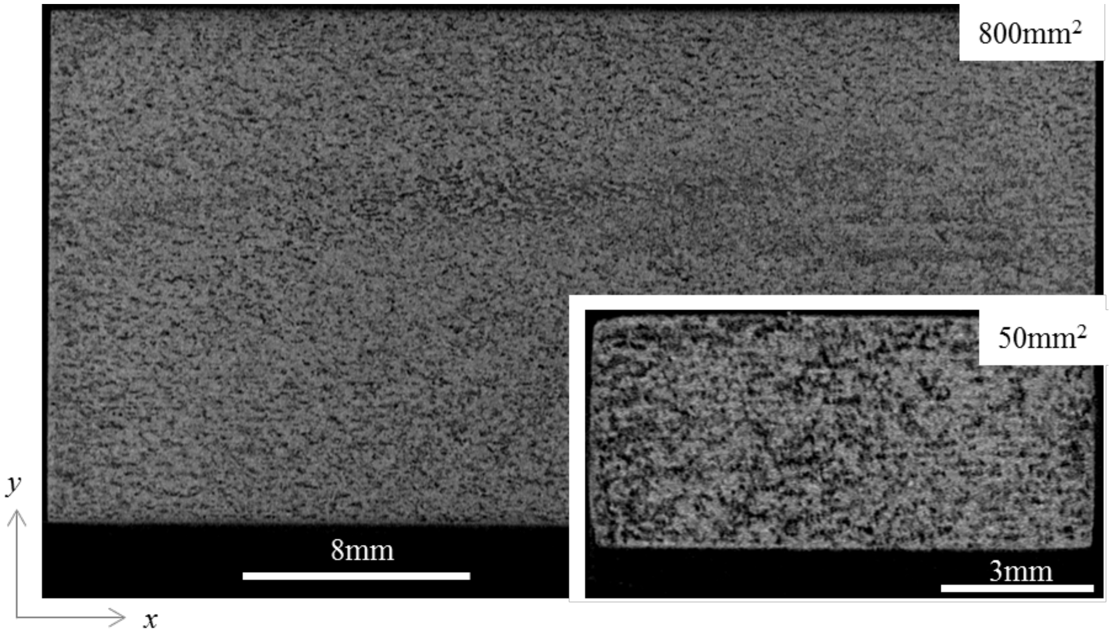

Fig.10 X-ray CT image of horizontal cross-sections of specimens which were obtained by low temperature process (z = 2.5mm). Brightness shows local density.

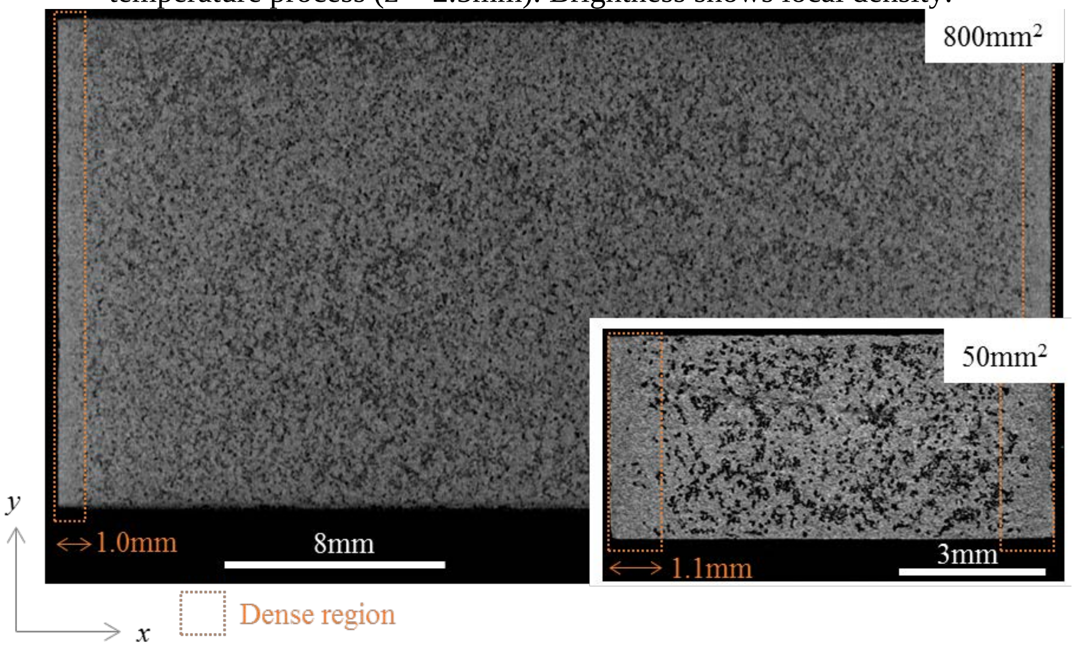

Fig.11 X-ray CT image of horizontal cross-sections of specimens which were obtained by high temperature process (z = 2.5mm). Brightness shows local density

Discussion

Influence of process time per layer on part quality

The density of part became higher as the layer time became shorter. The effect of changing layer time is stronger when the time is relative low. This tendency can be explained as following. In low temperature process, the greater part of energy for melting is supplied by the laser. The supplied heat for each layer stays in the scanned region and contributes to the process of the next layer also. Since the heat disperses until heat for the next layer is supplied, a long layer time decreases the contribution of previously supplied heat. And the density of the parts decreases.

Contrarily, in the high temperature process the powder bed is kept near melting point even if the laser has not been irradiated, and, as a result, the contribution of process is relatively low.

Influence of geometry on part quality

It was found that the density of the part was very much dependent on its geometry. This can be explained as follows. When powder is melted, molten plastic flows and fills the gaps between powder grains. The molten plastic needs a period of time to fill; temperature of plastic is required to be higher than the melting point for the period. In the low temperature process, the supplied energy and heat is dispersed to the surrounding powder. Since the dispersing rate is faster when parts are smaller, the density of low specimens are small. The dispersing speed also increases as the aspect ratio increases. Thus, the greater the aspect ratio is, the lower is the density.

Conclusion

The influence of geometry and layer time on part quality in low temperature laser sintering was tested. As general tendency in this study, low temperature laser sintering is affected by layer time and geometry in the horizontal cross-section. The density of part is higher when the layer time is shorter in the low temperature process. When the layer time was 5s, the density of the part was 95%, but when it was 45s, the density decreased until 82%. The influence of layer time is stronger when it is shorter, and becomes drastically small after 25s. On the other hand, the influence of the processing order in a layer is negligibly small. With respect to the part geometry, the density of part increases as the horizontal cross-section area of part increases, and the maximum difference was 6% in this paper. The density of part decreases as the aspect ratio of the part in cross-section increases.

On the other hand, in high temperature process, the density is affected by the part geometry when the scan length is longer.

Acknowledgment

This research is supported by “Strategic Innovation Promotion Program” Cabinet Office, Government of Japan and New Energy and Industrial Technology Development Organization.

References

[1] Beaman, et al, “Solid Freeform Fabrication: A New Direction in Manufacturing,” (1996)

[2] Dotchev et al, “Recycling of polyamide 12 based powders in the laser sintering process,” *Rapid Prototyping Journal*, **15** (2009) 192-203

[3] Kruth et al, “Consolidation of Polymer Powders by Selective Laser Sintering, ” Proc. of the 3rd International Conference on Polymers and Moulds Innovations (2008) 15-30
[4] Choren et al, “SLS POWDER LIFE STUDY,” Proc. Solid Freeform Fabrication Symposium 2001 (2001) 39-45
[5] Niino et al, “Feasibility study on plastic laser sintering without powder bed preheating,” Proc. Solid Freeform Fabrication Symposium 2011 (2011) 17-29
[6] Niino et al, “Low temperature selective laser melting of high temperature plastic powder,” Proc. Solid Freeform Fabrication Symposium 2015 (2015) 866-877
[7] Tontowi et al, “Density prediction of crystalline polymer sintered parts at various powder bed temperatures,” Rapid Prototyping Journal, vol.7, (2001) 180-184
[8] Majewski, Hopkinson et al, “Effect of section thickness and build orientation on tensile properties and material characteristics of laser sintered nylon-12 parts,” Rapid Prototyping Journal, vol.17, (2011) 176-180
[9] Pavan et al, “On the influence of inter-layer time and energy density on selected critical-to-quality properties of PA12 parts produced via laser sintering,” Polymer Testing, vol.61, (2017) 386-395
[10] Gibson et al, “Material properties and fabrication parameters in selective laser sintering process,” Rapid Prototyping Journal, vol.3, (1997) 129-136
[11] Jain et al, “Effect of delay time on part strength in selective laser sintering,” The International Journal of Advanced Manufacturing Technology, (2009) 43, 117-126
[12] Wegner et al, “Correlation of process parameters and part properties in laser sintering using response surface modeling,” Physics Procedia, vol.39, (2012) 480-490
[13] Yamauchi et al, “Low temperature laser sintering of PA powder using fiber laser” Proc. Solid Freeform Fabrication Symposium 2016 (2016) 2204-2216