Feasibility study on plastic laser sintering without powder bed preheating

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ABSTRACT

In a plastic laser sintering machine, the most part of power consumption is spent on heating of powder bed. The powder bed heating is essential to prevent parts from warping during the process. However metal laser melting is normally performed without such heating. During the process, warping is suppressed by fixing the parts to a base plate. In the present research, the same scheme was introduced to plastic laser sintering. A plate of 2mm was successfully obtained. Residual stress was completely relieved by annealing treatment of 30min and permanent deformation was negligible. A relative density of 90%, which is standard level of commercially available part, was obtained. Tensile and impact strength were limited to 1/2 and 2/3 of those obtained by normal process, respectively. Energy consumption of laser module in preheating free process is around 45MJ/kg, and complete robustness against power supply interruption was demonstrated.

Introduction

Tohoku Earthquake on March 11th 2011 and the following tsunami had entirely damaged power generation infrastructure which was ranging more than 400km along the Japanese north east coast. As a result, The Tokyo Electric Power Company, which normally provides the greater Tokyo area with approximately 40,000MW at that time of year, suddenly lost 25% of its power generation. To prevent a sudden and following chain reaction which might lead to entire blackout, the power company divided its service area into 5 sections and instituted daily *rolling blackouts* each of which lasts for three hours. Implementation of the rolling blackouts had been expected to last for 1.5 months, but, in reality, thanks to great effort for recovering power generation and saving energy consumption, it had not been take place since one week after its initiation until today (July 15th 2011). Temperature rising in summer, requirement for electricity is increasing, and Japan is facing the fear of rolling blackout again. This issue is not limited to the region which is directly struck by the quake or the tsunami, but involving whole Japan. After the quake, four nuclear reactors have been shutdown though they were not damaged by the quake or the tsunami. Two shutdowns are due to the anxiety that another earthquake or tsunami destroys other nuclear plants, and the other two are for routine inspection. Some reactors which were under inspection when the quake caused were not rebooted even now though their inspection was finished already. As a result, power companies request their customers to cut power consumption by 15% and announce that they will take partial blackout if excessive demand is expected, to avoid disastrous entire blackout.

With respect to plastic laser sintering, power shortage matters for two reasons. First, large power consumption of the process itself is problematic. Figure 1 depicts power consumption of modules installed in a commercially available plastic laser sintering machine (Semplice, ASPECT Inc., Tokyo JAPAN) in idling state after warm-up is finished. The machine has a relatively large build envelope of 550mm x 550mm. As shown here, the machine consumes approximately 4.2kW during idling, and more than 60% is spent on heaters which are controlling the temperature of powder.

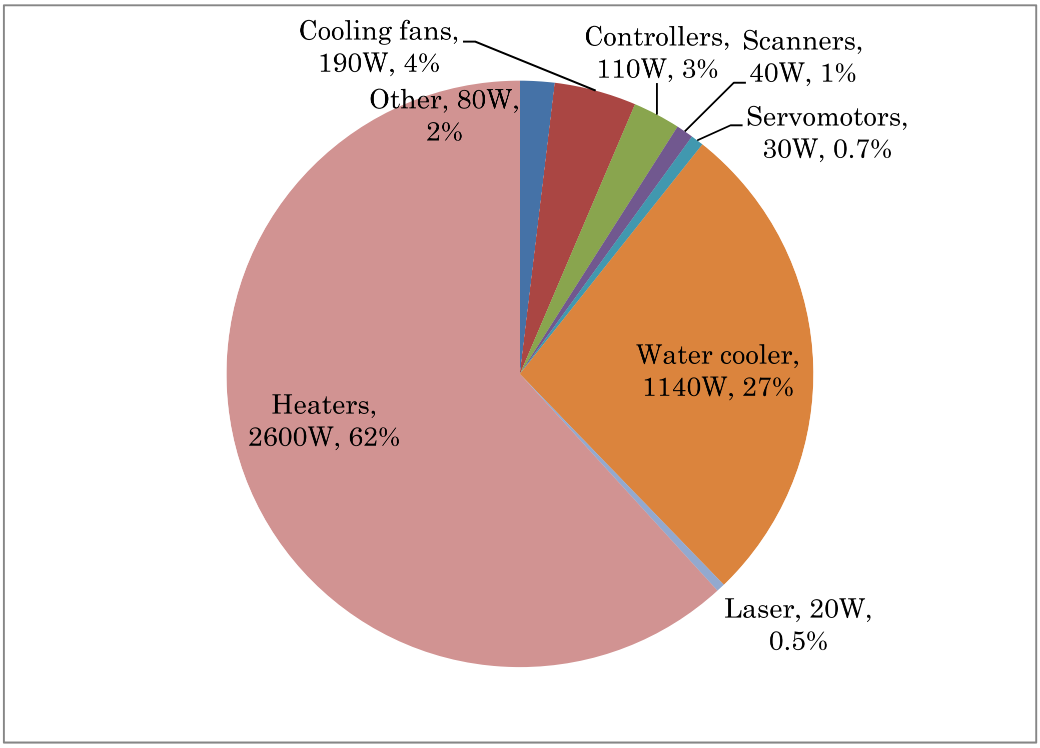


Figure 1 Power consumption of a laser sintering machine in idling state after warm up is finished.

For the second reason, interruption of electric service likely to happen in such tight energy condition, limits the maximum size that can be obtained by the process. In the process, the powder bed temperature is elevated between the crystallization and melting points of the powder, to reduce the generation of thermal stress [1]. Temperature drop during building process by some reason such as blackout results in irreparable part wapage, and the process resumption is impossible due to the collision between the powder supplying device (roller or blade) and the warping parts even after the temperature is recovered. Thus maximum size that we can obtain from plastic laser sintering is as much as we can finish while electricity service continues. In reality, many service bureaus in the greater Tokyo area were forced to stop providing large sized parts though their facilities had not been damaged by the quake or the tsunami.
In plastic laser sintering, powder bed preheating is performed to reduce generation of thermal stress by keeping the surface above crystallization temperature. On the other hand, in commercialized metal laser sintering or melting, preheating up to near the melting temperature is not implemented. Parts is fixed to a base plate not to warp [2] during sintering or melting process, and the residual stress is usually relieved by stress relieve annealing after the process.
The present research investigates feasibility of plastic laser sintering which does not use preheating but fixes the parts to a base plate. Reducing the power consumption for the preheating is expected to contribute to power saving dramatically. Additionally, absence of preheating might allow us interruption of laser sintering process. If we can restart part building after shutting down of the machine, robustness of the fabrication process is drastically improved.
Density of an obtained part is the primary index for its mechanical strength. The set of parameters that maximizes the density was searched for in experimental-based manner. In metal laser melting (sintering) processes, a supplemental and sacrificial structure known as anchor or support is used to fix the parts when the obtained parts should be separated from the base plate, or they have undercuts. These structures, if it is required, must be strong enough to resist the warping force, but, on the other hand, it should be as thin as possible for ease of following removal work [3]. Number of the supports should be as small as possible for the same reason, but large interval between supports results in local warpage. Design of support structure was optimized in terms of thickness and interval. The effects of stress relieve annealing were evaluated. Density and mechanical strengths of the parts were measured and compared with those obtained by normal laser sintering.

MATERIAL AND METHODS

POWDER, MACHINE, BASE PLATE AND PROCESS PARAMETERS

A commercially available polyamide powder (DuraForm PA, produced by 3D Systems) was used. A machine developed by the authors [4] was used. The machine is equipped with CO_2 laser source (GEM-30, Coherent Inc.), which can emit a single mode laser with a wave length of 10.6μm at the maximum output power of 30W. The laser beam is focused into a 130μm diameter ($1/e^2$) spot on the powder bed with a 109mm focal lengthed ZnSe lens. The beam can be scanned by a galvanometer mirror system in a range of 100mm×100mm. For powder supply, a roller system is used. The roller is 20mm in diameter and rotates with a DC servo motor. As this roller system is placed on a linear actuator which is driven by a stepper motor, rotation speed and direction of the roller can be controlled independently to traversing speed. In this research, typical counter roller mode was used.

The base plate and support structure should adhere tightly enough to resist strong warping force, which is generated when melt plastic is crystalized and cooled to room temperature. For this purpose, the base plate was made from the same material, i.e. DuraForm PA, by laser sintering. To prevent the plate from bending, the plate was attached to a 6mm thick aluminum alloy backup plate and fixed with screws as displayed in figure 2.

In the following experiments, laser power, scanning speed, scan spacing was varied to optimize the parameter and to investigate the relationship between the parameters and the obtained performance. Layering thickness and roller traversing speed and rotating speed were set at 100μm, 50mm/s and 150rpm, respectively.

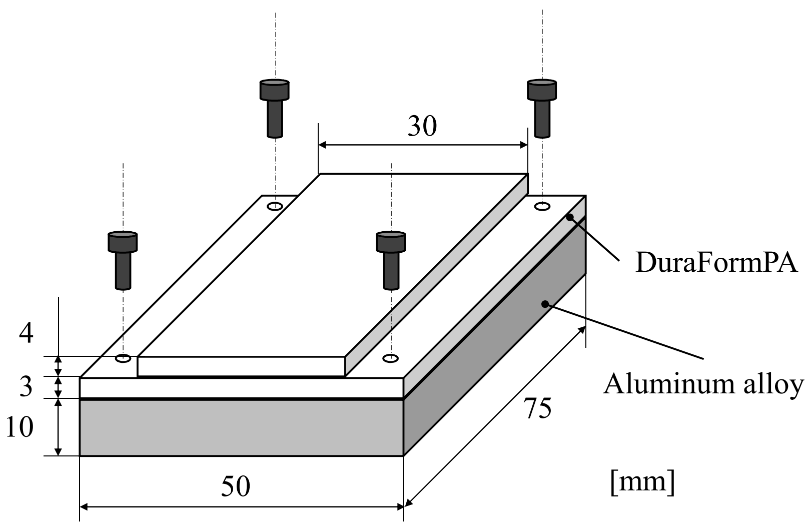


Figure 2 Base plate structure

PART DENSITY OPTIMIZATION

Part density optimization was performed by building coupons with various process parameters and comparing obtained densities. As the design of coupon, a thin plates of 20mm×30mm×2mm was used. To process this coupon, 19 layers of laser scanning were performed. Thus, it was always thicker than 18mm, and actual thicknesses were varying between 19mm and 20mm. We use relative density ρ_r, which is calculated as:

$$\rho_r = \frac{m}{v_a \times \rho_s} \tag{1}$$

where m, v_a and ρ_s are mass of a coupon, actual volume of the coupon and specific gravity of the powder material (0.97g/cm^3 for DuraForm PA).

OPTIMIZATION OF SUPPORT STRUCTURE

A 1mm high mesh type support structure as illustrated by figure 3a was used. To optimize the width of the support, w_s, overhang and support model as displayed in figure 3b was used and various support thickness were tested. Various gaps between supports, g_s, were tested, and warpage between neighboring ribs was observed to find support density requirements.

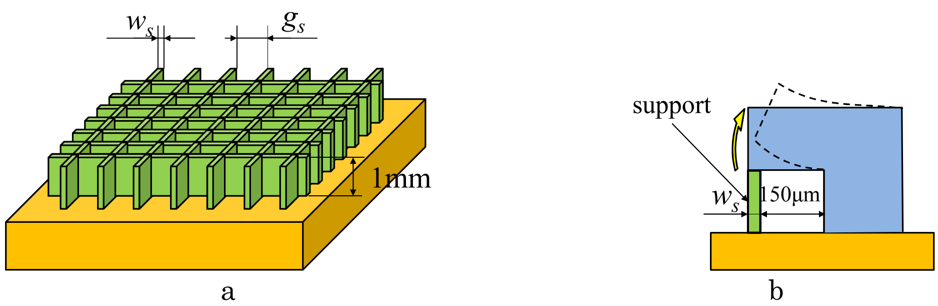


Figure 3 Mesh type support structure and its parameter optimization

RESIDUAL WARPAGE AND EFFECT OF ANNEALING

Support can prevent undergoing parts from warping, but the parts might deform when they are removed from supports due to residual stress. Warpage by the residual stress was measured by building test pieces of 50mm×10mm×2mm. Annealing at 80°C was carried out for 30minutes and the effect was evaluated. For annealing, an industrial programmable oven, DO-450PA, was employed. This oven is installed with 1.3kW of electric heater and possible to elevate the temperature of its chamber of 450mmx400mmx450mm up to 270°C.

STRENGTH MEASUREMENTS

Tensile and impact tests (ISO 527 and 180, respectively) were carried out. Since standardized specimen for tensile test could not be obtained due to build envelope limitation, specimen design as displayed in figure 4 was used. Build direction of each specimen was rectangular to the pulling direction in the tensile tests. The results were compared with those data of normal preheating process. For fabrication of normal processed parts, a prototype machine (beta version of Semplice produced by ASPECT Inc.) was employed. The process parameters were tuned so that the relative density becomes 90%, which is equivalent to a density value obtained without preheating. The parameters for the normal process with preheating are summarized in Table 1.

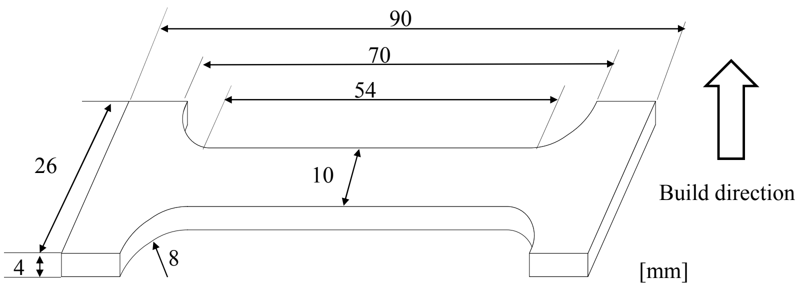


Figure 4 Tensile test piece

Table 1 Parameters for process with preheating

Beam power at the surface of powder bed	13 W
Scan Speed	3.78 m/s
Scan Spacing	150 μm
Powder Bed Temperature	177 °C
Density	89.70%
Tensile Strength	43.3 Mpa
Impact Strength Unnoched Izod	24.2kJ/m^2

BLACKOUT SIMULATION TEST

Confirm the advantage of laser sintering without preheating, a test as following was carried out.

1. On a 1mm high support mesh, a 20mm×30mm square shape coupon is built up to the thickness of 2mm (19layers).
2. Process is stopped and kept suspended for 30minutes.
3. Restart the process to finish another 20layers.
4. Defect on the interruption is observed visually.

ENERGY CONSUMPTION MEASUREMENT

As a result of quitting preheating, laser must supply more energy than when preheating was performed. This increase should be smaller than energy consumption to let the preheating free process be energy saving. Power consumption of the laser system at each laser power was measured by clamping its power line with a current tester (HIOKI 3293-50), and energy consumption was calculated by simply multiplying the read of the tester by 100V, outlet voltage in Japan.

RESULTS

PART DENSITY OPTIMIZATION

Relative density of typical laser sintered plastic parts is above 90%. In this research, parameters that can provide an equivalent density were searched for. Laser scanning speeds, v_L, and scan pitches, p_s, as listed in table 2 were used. Laser power at the powder surface, P_L, was varied up to the maximum value of 17W. Figure 5 depicts relationship between relative density ρ_r of energy irradiation per unit area e_a, which can be calculated as:

$$e_a = \frac{P_L}{v_L \times p_s} \tag{2}$$

As supplied energy density increases, density of part increases as general tendency. The maximum density of 93% was obtained when $e_a = 203\text{kJ/m}^2$. Supplying large energy colored the parts and made them brittle. A parameter set of P_L=7.5W, $v_L = 1.5\text{m/s}$ and $p_s = 30\mu\text{m}$, which brings a density of 90.9%, was selected as the default parameter set and used in the following discussion unless otherwise noted.

Table 2 Parameters for part density optimization

Scan speeds [m/s]	0.92, 1.53, 3.81
scan spacings [μm]	20, 30, 40, 50

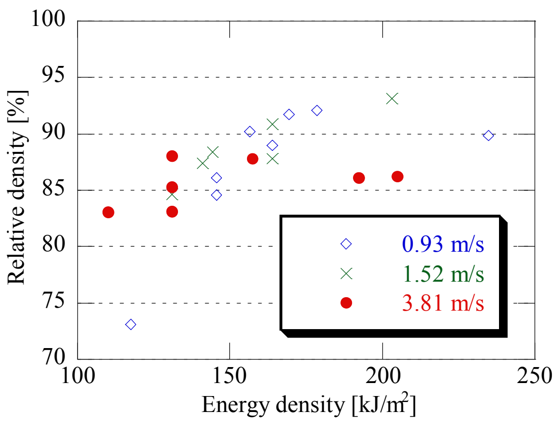


Figure 5 Relationship between relative density and energy irradiation per unit area

OPTIMIZATION OF SUPPORT STRUCTURE

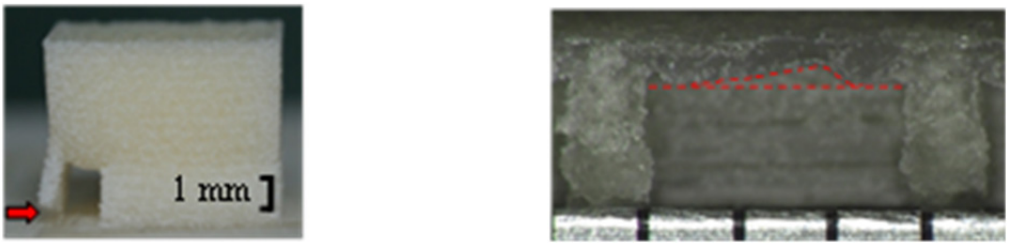
Table 3 summarizes characteristics of supports with various thicknesses. Nominal thickness is the distance between the center lines of the outermost scans. Though the distance between the center lines of scans is discretized by scan spacing (30μm as default), we neglect the difference between nominal thickness and real distance of outermost scans to simplify our discussion. Additionally, actual thickness is thicker than nominal thickness due to excessive sinter as listed in table 3.

Support with nominal thickness of 300μm was strong enough to support fine structure at the middle of the parts but did not stand curling force at the edge as shown in figure 6b. Secure support was obtained when its thickness was 0.4mm or thicker.

Small warpage between supports is likely to occur along the edge of the coupon. It started to occur around the test piece when the gap became larger than 2.0mm, and intruded into the middle section when it is larger than 3.0mm. For ease of support removal, default gap between supports was set at 2.5mm and an extra support was placed along the outline of the part.

Table 3 Strength of support

thickness [μm]		strength	usage
nominal	actual		
100		impossible to build	NA
200	390	tear off easily	NA
300	530	able to be tore off by pulling with tweezers	fine structure at the middle
400	610	strong	general
500	700	very strong	outline



a broken support at the edge b warpage between support

Figure 6 Failure of support

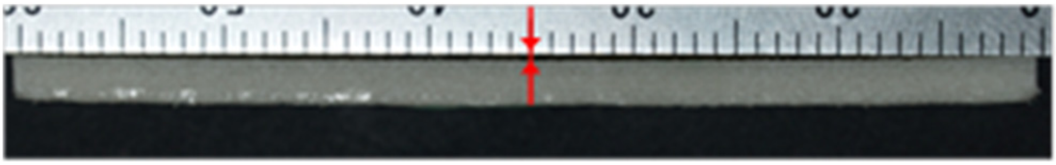


Figure 7 Warpage after build

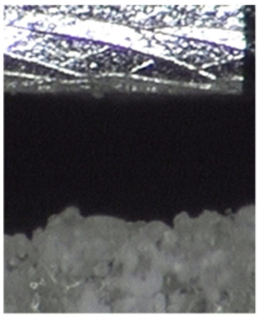
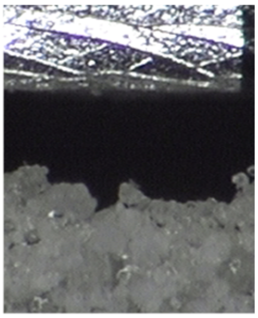
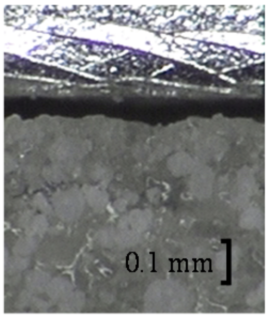
as sintered	left 30min	annealed
		
0.24 mm	0.20 mm	0.03 mm

Figure 8 Warpages after removing from the base plate

RESIDUAL WARPAGE AND EFFECT OF STRESS RELIEVE ANNEALING

Figure 7 shows typical appearance of warpage after a part is removed from its base plate. Figure 8 compares warpage when removed as soon as the sinter process is finished, 30 minutes after the sinter process and after 30min annealing at 80°C. As shown here, annealing treatment is a quite effective countermeasure against residual deformation.

STRENGTH MEASUREMENT

Table 4 lists process parameters that were used in the strength measurements. Figure 9 shows ultimate tensile strength for the process conditions. As shown here, tensile strengths are around 21MPa, and difference between conditions is very rare. As an overall tendency, the tensile strengths obtained by preheating free laser sintering are the half of those by the process with preheating using parameters (43MPa as shown table 1).

Figure 10 shows impact strength (izod unnotched) for the same process parameters as tensile tests. In these results, we can find clear superiority with condition 3, which is slower in scanning speed, narrower in scan spacing and lower in laser power. The impact strength obtained by this parameter set, 16.7kJ/m^2 in average, reaches 2/3 of those obtained by normal process with preheating (24kJ/m^2 as shown in table 1).

Table 4 Parameter sets used in strength tests

Condition	Scann speed [m/s]	Scan spacing [μm]	Laser power [W]	Energy density [kJ/m^2]
1	1.53	30	7.5	163
2	1.53	50	10.8	141
3	0.92	30	4.9	178
4	0.92	50	7.5	163

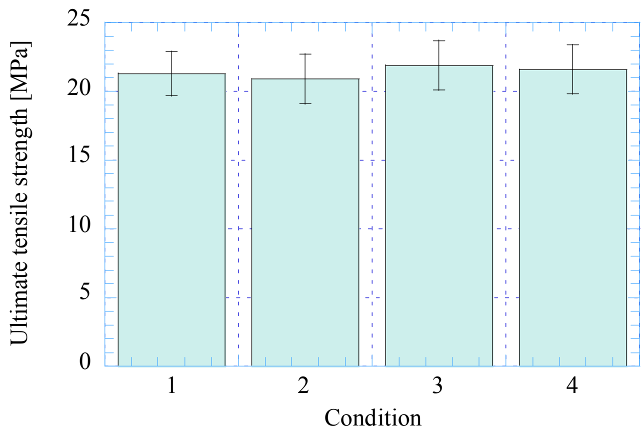


Figure 9 Ultimate tensile strengths in various conditions

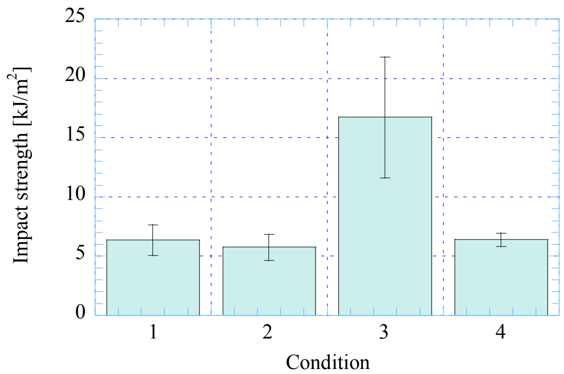


Figure 10 Impact strengths in various conditions. Izod unnotched (ISO 180)

BLACKOUT SIMULATION TEST

Figure 11 shows a closed-up side view of a part whose process had been interrupted for 30min to similate a blackout. As far as observing visually, we do not find defect or difference in suspended layer..

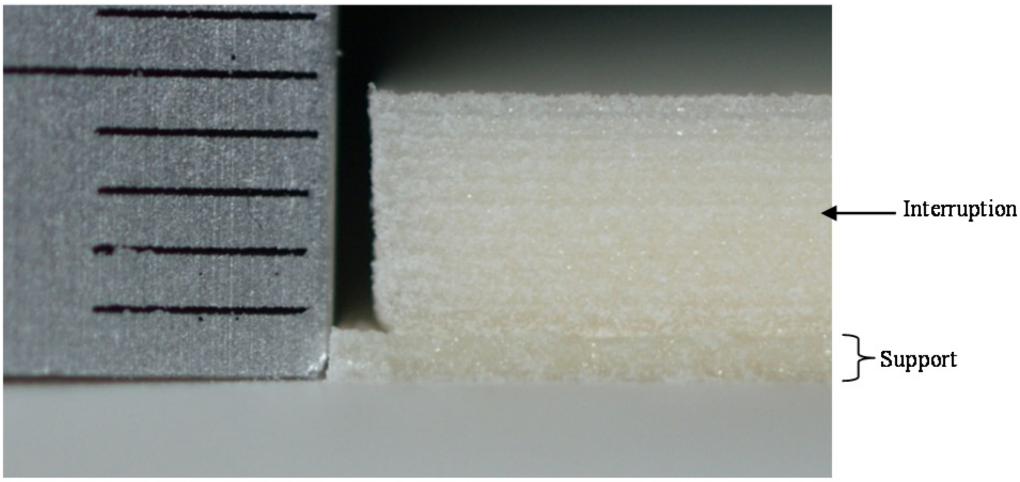


Figure 11 Closed-up side view of a part whose process was interrupted for 30min. Suspended layer is indexed by the arrow.

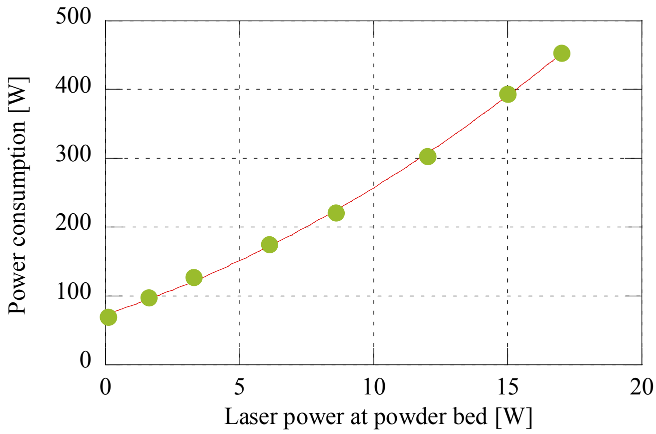


Figure 12 Relationship between energy consumption and laser irradiation at powder bed

Energy consumption measurement

Figure 12 is relationship between power consumption, P_c[W]and laser intensity on the powder bed, P_L[W]. This relationship can be approximated by a parabolic function as:

$$P_C = 0.556P_L^2 + 12.9P_L + 73.2 \tag{3}$$

Though power consumption for $P_L = 0$ is 73.2W according to this formula, actual power consumption which was measured while the laser was idling was 23.4W.

DISCUSSIONS

Mechanical performance

Achievement of the high relative density more than 90% demonstrates that powder is successfully melted and a high flowablity of the molten plastic was obtained as well. Large deterioration in tensile strength despite the high relative density is an issue to be considered. Since the temperature of substrate, the previously sintered layer, is colder than the case of preheating process, delamination between layers seems to occur more easily. However, since the pulling direction is rectangular to lamination, delamination does not seem to play dominant role in the degradation of the tensile strength in the direction. There might be two possible reasons. One is difference in microstructure [5], and the other is degradation of material performance. Latter suspicion is supported by deterioration in impact strength as general tendency. In addition, smaller decrease of impact strength when laser power is relatively low indexes that irradiation of highly intense laser might play important role in low mechanical performance of laser sintering without preheating.

WARPAGE PREVENTION

As far as building thin objects such as the test piece in the present research, prevention of warp distortion by using support structure is successful and satisfying. However, effectiveness for such a thick and large object that it takes more than a day to finish its building is not clear. To reveal the feasibility of such applications, more analytical study and quantitative measurements of warpage and warping force is required.

We can expect that creeping ability of plastic facilitates the fabrication of large object without preheating than metallic materials.

POWER SAVING ASPECT

Table 5 summarizes the laser power at powder bed, P_L, power consumption, P_c,, irradiation time per unit volume, τ_{Li}, and energy consumption per unit volume, e_{Lc}. Irradiation time per unit volume and energy consumption per unit volume can be obtained by following calculations as:

$$\tau_{Li} = \frac{1}{v_s \times p_s \times t_l} \tag{4}$$

$$e_{Lc} = \frac{P_c}{\tau_{Li}} \tag{5}$$

where t_l is layer thickness. Energy consumptions by the laser module in preheat free and preheat process is displayed in table 5. As shown here, energy consumption of laser in preheating free process is almost 8 times of that in preheating process.

Literature [6] estimates the energy consumption of a normal plastic laser sintering machine as 53MJ/kg. This is comparable to the consumption of the laser.

Table 5 Energy consumption example of processes with/without preheating. Power consumption of laser unit is obtained from laser power at powder bad using formula 3.

Parameters	preheat free	preheat
Laser power at powder bed [W]	7.5	13
Power consumption of laser unit[W]	201	335
Scan speed [m/s]	1.5	3.78
Scan interval [μm]	30	150
Layer thickness [μm]	100	100
Irradiation time per voluum [s/cm^3]	222	18
Energy consumption by laser per voluum [kJ/cm^3]	45	6
Energy consumption by laser per mass [MJ/kg]	43	6

CONCLUSION

Plastic laser sintering using support structures instead of powder bed preheating was proposed. It was shown that a plate with thickness of 2mm can be obtained, and part density met standard level of normal preheating process, 90%. Investigation of applicability to larger or thicker object requires further research. Residual stress can be completely relieved by annealing treatment for agreeable duration. Tensile and impact strength were limited to 1/2 and 2/3 of those obtained by normal process, respectively. Clear reason for this degradation was not obtained. Energy consumption of laser module in preheating free process is around 45MJ/kg, and complete robustness against power supply interruption was demonstrated.

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