Effect of Powder Compaction in Plastic Laser Sintering Fabrication

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ABSTRACT

Powder compaction is introduced into plastic laser sintering fabrication. Compaction was carried out by using a roller of which rotation speed is independently controlled of its traversing speed. This additional process improved packing density of powder bed by a factor of 20% and reduced residual porosity of obtained parts by a factor of 30%. As an advantage, powder compaction can improve mechanical strength of parts of semi-crystalline powder, but increases excessive sinter to reduce fabrication accuracy especially in fabrication of amorphous plastic. This paper presents characteristics of the powder compaction process itself and its effects on performance of obtained parts.

INTRODUCTION

Laser sintering freeform fabrication ("LS" in the following discription) is a relatively new technology among those processes that produce three dimensional objects from powdery material[1]. Although most of the other powder based production methods include compaction process before sintering, powder in LS is not explicitly compressed. There are many reasons for this difference. Difficulty in adding such function to LS systems due to complexity of mechanism and high temperature in their process chambers to fulfill the laser sintering process are two reasons for the absense of a compacting process. On the other hand, less neccessity of compacting in LS than the other powder sintering processes, in which powder must be compressed by high pressure to form green parts, is another reason. However, the advantage of powder compaction in LS has not yet denied. In this paper, an experimental method that enables powder compaction without adding major change in mechanism to commercially available system is introduced. The method is tested and improvement in density of the powder bed is measured. Porosity and mechanical properties of processed sinters are evaluated. Effect of different powder material characteristics is also discussed; Both of semicrystaline plastic, PA12 (DuraForm® PA), and amorphous plastic, Polystyrene (CastForm® PS), are tested, and difference in effect of compaction is discussed.

POWDER COMPACTION

COMPACTION METHOD AND DEFINISIONS

Compare to normal powder press applied to form green parts using a mold the cross section of powder bed in LS system is much larger, thus it is difficult or almost impossible to provide the powder bed with a high pressure (a large pressing force) at one time with a piston or a flat plate. Instead of such devices, a roller, which is utilized to spread powder by its counter-rotating motion[2] (Fig. 1(a)) can be applied in some LS systems. To compact powder bed, we should not rotate the roller in the counter direction as we often find but in the right direction as shown in Fig. 1 (b). This roller operation introduces powder below the roller to increase the amount of powder under the roller in comparison with the opposite rotational direction's case, and applies presseure to the powder bed resultantly. Fig. 2 shows result of compaction with right-direction-rotating roller. As shown here, craters occur on the powder surface. These craters are created since the powder is compressed so much that the compressed lump of the powder sticks on the roller surface. This problem can be solved by limitting the amount of powder in front of the roller. More specifically, recoating process should follow the scenario shown in Fig.3. For the first, part piston is lowered by a depth
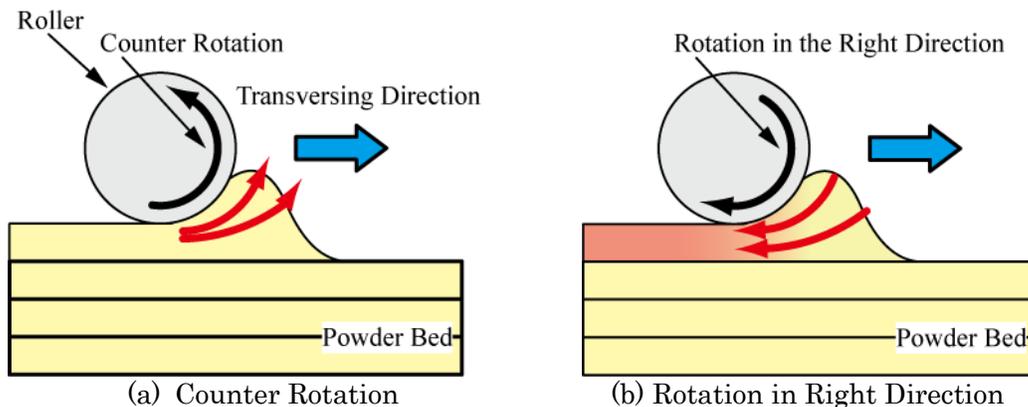

(a) Counter Rotation   (b) Rotation in Right Direction

Fig. 1 Two types of roller operations

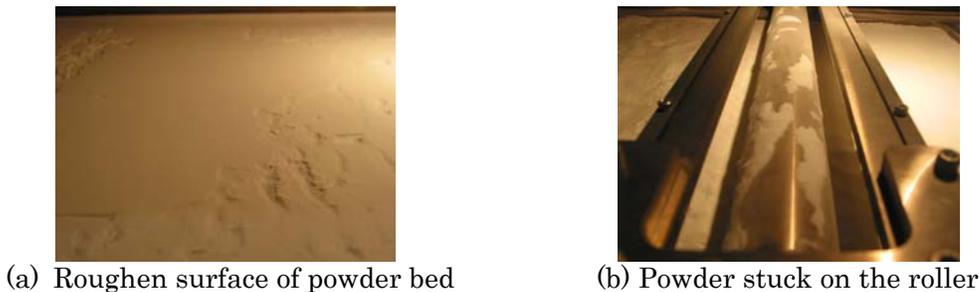(a) Roughen surface of powder bed   (b) Powder stuck on the roller
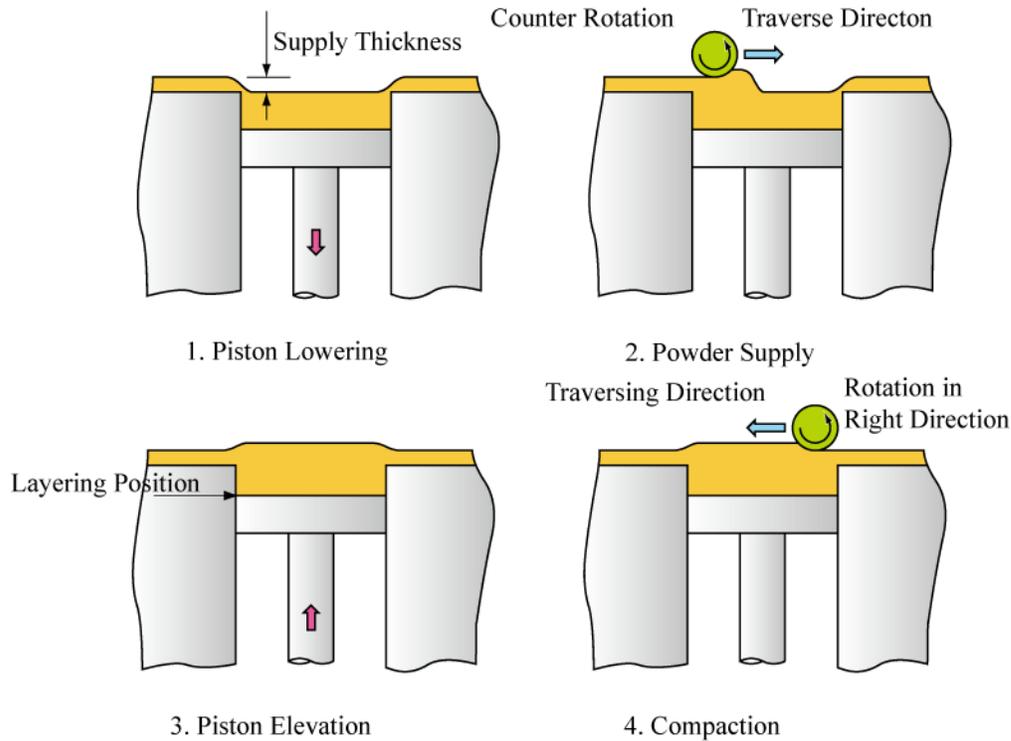
Fig. 2 Recoating with roller rotating in right direction

Fig. 3 Compacting Method

(supply thickness, d_s, in the following description) that is larger than layer thickness, d_l. Then, counter-rotating roller spread the powder and fill the gap created by part piston's lowering in the previous procedure. Reversely, the piston is raised up to the level that is lower than the initial state by the layer thickness. Finally, the roller traverses the powder bed to compress the powder as rotating in the right direction. Here, we difine "Compaction Factor," f_c, as

$$f_c \equiv \frac{d_s}{d_l} - 1 \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots ①$$

Compaction factor indicates how much the powder bed is compacted, and it becomes zero when supply depth and layer thickness becomes the same.

PACKING DENSITY OF UNSINTERED POWDER

To evaluate improvement in packing density of powder by the compaction method, experiments using an LS system were carried out. A hollow box as shown in Fig. 4 is built and packing density, ρ_c, of the unsintered powder (cake in the following description) remaining in the cavity is calculated by following fomula.

$$\rho_c = \frac{m_f - m_e}{V_c \, \rho_t} \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots ②$$

where m_f, m_e, V_c and ρ_t are mass of the built box including the cake, mass of the emptied box, volume of the cavity calculated from measurement of its inner dimensions and specific gravity of the powder material, respectively.

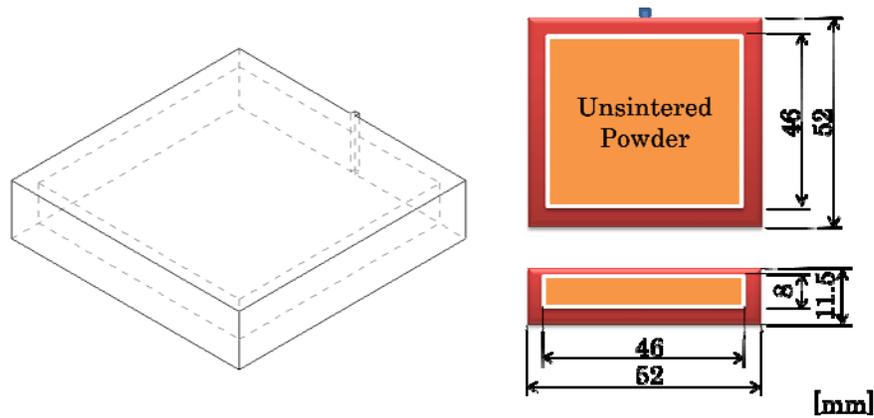Fig. 5 shows relationship between, packing density and compression factor. In these

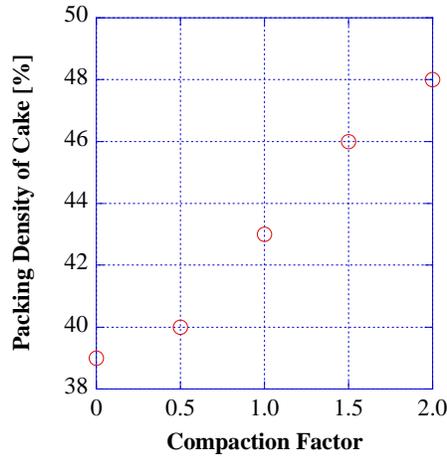Fig. 4 Test specimen for packing density measurement

Fig. 5 Relationship between Packing Density and Compaction Factor

Tbl. I Characteristics of PA powder

Average grain size	58μm*
Apparent Density (ISO 60)	0.42 g/cm³ (40%)
Tapped Density	0.50 g/cm³ (50%)
Specific gravity	1.00 g/cm³*

*Data provided by 3D systems

experiments, a polyamide powder (DuraForm® PA from 3D Systems) is used. Tbl. I summarises characteristics of the powder. A prototype version of Semplice (ASPECT Inc.), which is equipped with a roller system that can control rotation speed and travesing speed of the roller independently, was employed. Layer thickness of 100μm was selected. Traversing speed, v_{ct}, and rim speed, v_{cr}, of the roller during compacting process share the same value of 100mm/s to avoid friction between the roller and powder bed. Packing density increased with compaction factor and   reached the highest value of 48% when f_c = 2.0. This value is larger than in the case that compaction is not applied but still lower than tapping density of 50%. Higher compaction factor causes failure such as crater and drag of the part bed.

Fig. 6 shows relationship between packing density and translating speed of the roller in various compaction factors. The lower roller speed is, the higher packing density becomes. We can find that the highest density is 49% when v_{ct}=50mm/s and f_c = 2.0. However, this compaction condition cannot be used since it causes drag of the previous layer at a certain provability.

ROTATION SPEED OF ROLLER IN COMPACTION PROCEEDURE

In experiments of the previous section, rotation speed of the roller was controlled so that its rim speed becomes the same. Following is discussion on phenomena that occur when the two speed do not match.
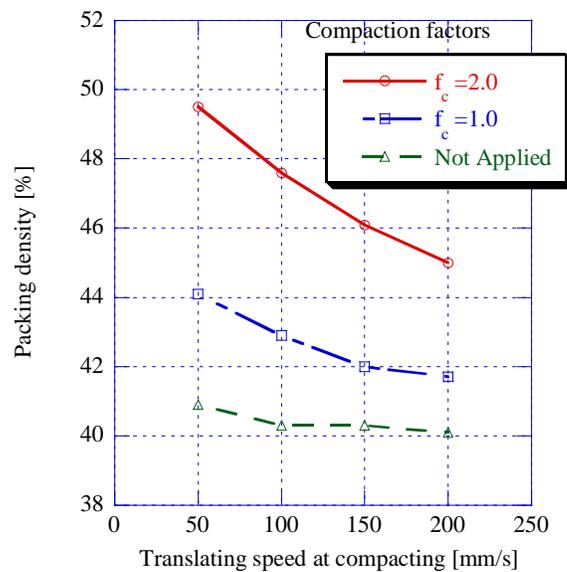

Fig. 6 Relationship between packing density and transverse speed

Fig. 7 includes side views of sinters obtained in various conditions of rotation speed and traversing speed. Translating speed of 50mm/s was used for photos (b) through (e). Rim speed was varied. Compaction factor is 2.0 for all photos. The LS system employed in this research has a pair of feed cylinder on the both sides of its part cylinder. In normal process without applying compaction process, the both cylinders are used alternately. Contrary, when compaction process is added, the roller go from one side to the other to spread the powder, and returns to compact the bed. Thus, only one side of the feed cylinders is used if we do not switch the spreading and compacting direction intentionally.   Since capacity of a feed cylinder of the employed machine in this research is insufficient to complete one test piece, the feed cylinder is switched during a build. Bold lines in the pictures in Fig. 7 display layer where the directions were switched, and arrows indicate the compacting directions. Followings are explanations for results sown in Fig. 7.

(a) $f_c = 2.0$, $v_{ct} = v_{cr} = 100$mm/s

Refference for successful build.

(b) $f_c = 2.0$, $v_{ct} = 50$mm/s, $v_{cr} = 25$mm/s

Previously built object is dragged in the forwad direction.

(c) $f_c = 2.0$, $v_{ct} = 50$mm/s, $v_{cr} = 0$mm/s

Drag in the same direction is observed but is milder since not rotating roller does not introduce so much powder.

(d) $f_c = 2.0$, $v_{ct} = v_{cr} = 50$mm/s

Although the rubbing between the roller and bed is minimized, small drag is still observed. We cannot find the relation between the direction of the drag and roller motion. As a result of compressing large amount of powder under the roller, pressure rose to very high level, and a friction force drags the previous layer in an unpredictable direction.

(e) $f_c = 2.0$, $v_{ct} = 50$mm/s, $v_{cr} = 100$mm/s

Since rim speed is faster than traversing speed, drag in the backward direction occurred.

(a) $f_c = 2.0$, $v_{ct} = v_{cr} = 100$mm/s

(b) $f_c = 2.0$, $v_{ct} = 50$mm/s, $v_{cr} = 25$mm/s

(c) $f_c = 2.0$, $v_{ct} = 50$mm/s, $v_{cr} = 0$mm/s

(d) $f_c = 2.0$, $v_{ct} = v_{cr} = 50$mm/s

(e) $f_c = 2.0$, $v_{ct} = 50$mm/s, $v_{cr} = 100$mm/s

Fig.7 Drags caused in various roller speed conditions

From these results, we obtained the following conclusions.

1. We should equalize the roller's rim speed with its translating speed to avoid drag.

2. Insufficient and excess speed of the roller results in the drag of the lower layers in front and back, respectively.

3. High packing density raises the provability of drag even if rim speed is in accordance with traversing speed.

EFFECT OF POWDER COMPACTION

IMPROVEMENT IN PACKING DENSITY OF SINTER

Fig. 8 shows relationship between packing density and compaction factor at various laser powers. The packing density was obtained by meausrement of mass and dimensions of test specimen. Packing density increses with compaction factor unitil $f_c > 1.0$. When $f_c > 1.0$, the density decreases in turn since amount of excessive sinter became large. The maximum packing density is 94% while one at the same building condition without compaction is 91%. Though improvement of 3% in packing density seems quite small, relative reduction rate in porosity of 33% is not a small value.

REDUCTION OF CURL DISTORTION

In this section, we discuss the effect of powder compaction on occurrence of curl distortion. Cubic specimens with dimensions of 4mm $\times$ 10mm $\times$ 80mm were built from PA12 powder. Heat barriers, thin disks which are built below objective sinter for the purpose of preheating, were not used to obtain measurable distortion. Photos for the specimens built in the both conditions are shown in Fig. 9. Curl distortions were successfully suppressed, and the measured value when compacting is applied and not applied are 0.3mm and 0.8mm, respectively.

We can roughly categorize curl distortion into two groups. The first one includes curls that are caused during repeating powder supply and laser exposure. We name this type of curls as "curls in process". The other one includes those that occur during cooling stage of the powder bed, after layering is finished. We call this category as "curls in cooling." Since curls in cooling occur after objects are build correctly, thickness is constant over all the area when a flat plate is built as shown in Fig. 10(a). On the other hand, the plate is thinner near the edge in the case of curls in process as shown in Fig. 10(b), since the curls of the layer occurred earlier, i.e. lower layer, is larger. In LS process, solidification of melted or

partially melted powder on the objects being solidified previously, repeats in layer by layer fashion. Since solidification involves shrinkage, LS includes process to generate curl distortion inherently. To avoid this dilemma, various countermeasures are taken in commertially available systems and materials. Among these measures, controlling reduce the curls. LS system's recent trend toward scalling-up of build-envelope raises difficulty of precise temperature control over the whole build area. If powder compacting can reduce the
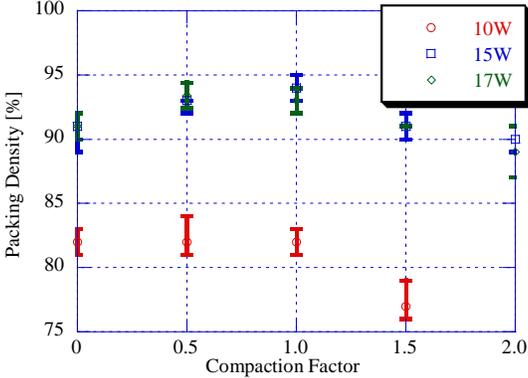

Fig. 8 Relationship between packing density of sinter and compaction factor

a. Top view   b. Side view

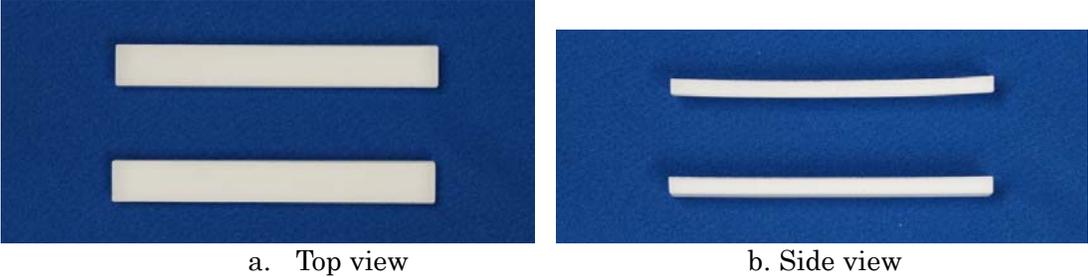Fig. 9 Photos of specimens for curl distortion measurement. Top: without compacting, Bottom: with compacting.

a. Curl in cooling $(t_c \approx t_e)$ b. Curl in process $(t_c > t_e)$
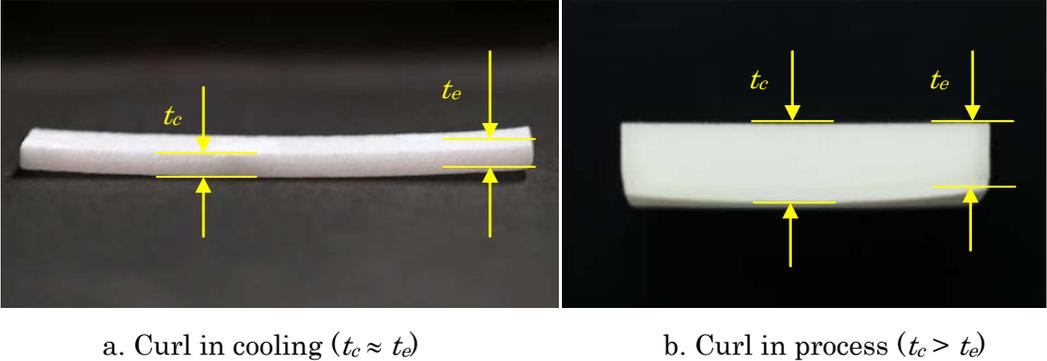
Fig. 10 Two types of curl distortion

curl distortion when powder bed temperature is out of the range, application of compacting is helpful for development of today's large scaled machines. To evaluate this effect, cubes with dimension of 52mm×52mm×11.5mm were built at various temperature. The results are listed in Tbl. II. Tbl. III shows curls of the specimen built at 165°C. As shown here, powder compaction successfully reduced the distortion that was caused by insufficient powder bed temperature. Though residual curl of 0.2mm when compaction is applied is not acceptable yet, this can be suppressed by taking other supplementary countermeasures such as heat barriers. This result demonstrates that powder compaction can expand the width of the process window from 5K to 10K.

IMPROVEMENT IN MECHANICAL PROPERTIES

Effect of powder compaction on improvement in mechanical properties was investigated.

Tbl. II Building Result in Various Temperature Conditions

Powder bed temperature [°C]	Result
180	Powder bed melted.
175	Good
170	Good
165	Building is finished, but curl occurred.
160	Collision between roller and sinter. Building was failed

Tbl. III Reduction of curl in building at 165°C

Compaction Factor	Cake Density [g/cm³]	Sinter Density [g/cm³]	Height at the center [mm]	Height at the edge [mm]	Curl [mm]
No Compaction	0.40	0.91	11.3	10.6	0.7
2.0	0.46	0.92	11.5	11.3	0.2

Tbl. IV Improvement in Mechanical Strength

	w/o Compaction	with compaction	increase	Rate of increase
Yield Stress [MPa]	42.0	44.0	2.0	5%
Elongation @ break [%]	13.8	14.4	0.6	4%
Flexural stress [MPa]	51.1	56.1	5.0	10%
Flexural Modulus [MPa]	1178	1347	169	14%
Impact strength (not notched) [kJ/m²]	27	36	9	33%

Tensile test (ISO 527), three-point bending test (ISO 178) and Izod impact test (ISO 180) were performed (Tbl. IV). Impact strength improvement is the most significant, and others such as bending are following. Performances against tensile stress are also improved, but the extent of improvement is much smaller. In comparison with a small improvement in density of 1% the strength is relatively large although a strong relationship between packing density and mechanical properties of a powder [3]. Here, we can guess that compressing force during compacting process increased adhesion between grains or layers. In addition, better improvement in strength against bending than against pulling indicates that improvement of the adhesion between layers occurred, and it supports our hypothesis that pressing force is major cause of strength improvement.

COMPACTION OF AMORPHOUS PLASTIC

Although LS process is applicable to all thermoplastics in principle, choices of plastics that can be used for fabrication of structural parts are quite limited to some semicrystaline polymers such as polyamide and polypropylene. In this section, we discuss the application of powder compaction to LS process of amorphous plastic which is mostly used for fabrication of lost models for casting.

IMPROVEMENT IN PACKING DENSITY OF POWDER

Polystyrene powder (CastForm™ PS, 3D Systems) is used in the following tests. Tbl. V shows characteristics of the powder compared to polyamide powder discussed in the previous section. Tbl. VI shows the improvement of density of the powder bed. For calculation of packing density, specific gravity of 1.05g/cm^3 is used as typical value for polystyrene. A compaction factor of 1.0 can raise the packing density from 39% to 44% (0.46g/cm^3 in density). This value is equivalent to tapped density. Compaction at higher compaction factor was not successful. These experimental results show that PS powder can be compacted more easily than PA powder. We can not specify where this difference derived from; nature of the materials or acquired characteristics when the material is shaped into powder grains.

IMPROVEMENT IN DENSITY OF SINTER AND EXCESSIVE SINTER

Density of processed sinter is measured. As a test specimen, a cube with dimensions of $52\text{mm} \times 52\text{mm} \times 11.5\text{mm}$ is used. Tbl. VII shows packing density and dimensions of

Tbl. V Characteristics of PS powder

	PS	PA
Average grain size	62µm*	58µm*
Apparent Density	0.40 g/cm³	0.40 g/cm³
Tapped Density	0.46 g/cm³*	0.50 g/cm³

* Data provided by 3D Systems

Tbl. VI Packing Density of PS powder after compaction

	Packing Density of Powder	
Compaction Factor	PS	PA
Not applied	39%	41%
1.0	44%(46g/cm³)	44%
2.0	-	46%

Tbl. VII Packing density and dimensions of sinter of PS powder

Compaction	Width in x axis	Width in y axis	Width in z axis	Packing density
Not Applied	51.6mm	51.6mm	11.9mm	53%
f_c = 1.0	51.8mm	51.6mm	12.1mm	56%

processed sinters. Compaction of $f_c = 1.0$ improved density of sintered by 3% to 56%. This packing density is still so low that we cannot use these sinters as structural parts. In addition, compacting adds excessive sinter reducing accuracy of the parts.

We can conclude that compaction does not bring positive change to process with amorphous plastic.

DISCUSSIONS

Though, in this research, counter-rotating roller is employed for powder spreading, we can replace this mechanism with a simple blade and place it just before the compacting roller. Then, powder spreading and compaction is performed simultaneously in a single roller traversing action. This will be able to halve the recoating time, consequently.

Compacting phenomena having been discussed in this paper requires elasticity of the powder or roller mechanism. Otherwise, compaction factor must be equal to increase rate of powder density. Fig. 11 explains the case that elasticity of powder bed plays dominant
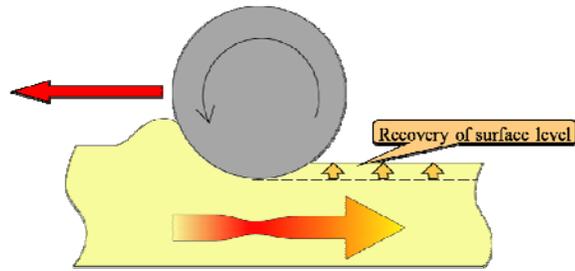
Fig. 11 Schematic view for compaction at high compaction factor

role in solving the problem. Surface level of powder bed before compacting roller is very high. When the roller runs over the high powder bed, the powder is once compressed so that the level is lowered to the bottom line of roller. In this moment, a large amount of powder exists under the roller, but the stress is relieved by deformation of the powder in the wide range around the roller. The deformation derives from plasticity and elasticity of the bed, and deformation owing to the latter one is released and powder level is partially recovered after the roller passed.

For analysis of compacting powder, we have to establish new analytic model in the future. Shanjani et al introduced a mathematical model [2], but the model is based on counter-rotating roller system though we need one for the roller rotating in the reverse direction. We find similar mechanism in powder rolling process and analytic model is provided [4, 5]. In this process, powder is compressed to form a seat as it is sandwiched and conveyed by a pair of rotating rollers. It seems possible to use this model for our mechanisms. However, modification is still required since phenomenon is slightly different. For example, thickness of the seat is very much larger in our system. Speeds at which powder is involved and seat is rolled out are the same.

Quite interesting is that density of the unsintered powder bed is lower than apparent density when compacting is not performed. This means counter-rotating roller spreads and lays the powder quite loosely. This is quite adequate to recoating new powder in very thin layer uniformly without giving drag force to sinters in the previous layers. However, it is not good for adhesion since adding pressure is an essential prerequisite for adhesion. In that meaning, adding pressure after forming layer by counter-rotating roller is quite reasonable for the both of quality of layer and adhesion.

Compaction is quite effective on improvement of adhesion but increases excessive sinter as its drawback. Since these merits and demerits derive from the same phenomenon, we have to make some trading-off to use compaction process. It is quite dependent on the

characteristics of material, and in the case of amorphous plastic, we should not apply the new supplemental process.

CONCLUSION

An experimental compaction method was introduced. The method consists of two processes. In the first process, a counter-rotating roller spreads the powder, and in the later process, the part piston is heightened and rotor rotating in the right direction compresses the powder surface. This compaction process successfully raised powder density of the bed to its tapped density. To avoid drag of the powder bed, rim speed and traversing speed of the roller in compaction process should be equalized, and powder bed density should be lower than tapped density. In case of polyamide, powder compaction reduces the curl distortion and improves mechanical properties up to 33%. Reduction of curl distortion can double the width of process window of part bed temperature. Improvement of mechanical property derives from that in adhesion by adding pressure to the powder. Application of compaction to amorphous powder increases excessive sinter and we could not find its merit.

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