FULL-DENSIFICATION OF SLS PARTS BY RE-MELTING

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Abstract

Among commercially available rapid prototyping processes, SLS is the most effective in terms of adaptability of various materials. However, rapid prototyped parts by the process are always porous and the physical properties of the parts are different from dense parts which is to be used in final product. This paper introduces a post process that can densify SLS processed plastic parts to almost 100%. An SLS processed polystyrene part is densified and, resultantly, a much stronger and transparent part is obtained.

Introduction

Since market debut of stereolithography, various types of rapid prototyping processes and devices have been developed, and some are still being. In the early period of RP's history, the most effort was focused on how to build parts successfully without failure, and then how to make them accurately. However, recent discussions have shifted to how to realize good qualities other than accuracy such as tensile strength, heat resistance, chemical toughness and possibility of building out of special materials like metals or ceramics.

In terms of part build accuracy, stereolithography is superior to selective laser sintering (SLS). On the other hand, in many cases, SLS is more convenient because of its faster building speed and applicability to larger variety of materials such as high-temperature polyamide and easy-to-be-lost polystyrene. While SLS's good ability of building prototypes out of various plastics provides good estimation of chemical property of their product version, which is to be injection-molded in the most cases, prediction of physical or mechanical performances such as tensile strength is poorer because of inevitable porosity of SLS processed parts. For example, an SLS part out of CastForm PS are much more fragile than a typical injection-molded polystyrene part, and handling of the part requires great care if it is not reinforced by wax infiltration. From a viewpoint of estimating a prototype in advance of making die and mold, the prototype should be fully dense and made out of the same material as its product version.

Investment casting of plastics using plaster mold is a classical way of obtaining fully dense parts. However, it is not always easy to burn out the model especially when the structure of model is complicated. The authors propose a novel process to densify an SLS parts by wrapping it with plaster and then remelting.

This paper introduces the process for full-densifying SLS processed parts and reports process parameters of experimental densification of polystyrene parts. Some physical parameters such as tensile strength of densified parts are measured and reported.

Process

Fig. 1 shows outline of the process that can densify SLS processed parts. First, an SLS processed part is invested with plaster. After hardening the plaster, the investment including the SLS part is loaded into a vacuum chamber that is installed in an oven. The vacuum chamber is evacuated first, and then the oven's heaters are turned on to melt the parts. Doing these in this order allows the air out of the pore network in the SLS part to be removed before the molten resin out of the part blocks the network to leave isolated pore containing the air in the middle of the part; otherwise, bubbles would remain in the final densified part. In this process, the molten resin flows into the lower section of the plaster cavity and remain there, while, in investment casting process, it should flow out of the cavity instead. Since the original SLS parts are porous, the whole cavity cannot be filled up only with original model. To obtain desired shape of full-dense parts, a dummy volume out of the same material should be attached at upper part of the desired shape of the SLS part. The dummy can be built as a part of SLS model.

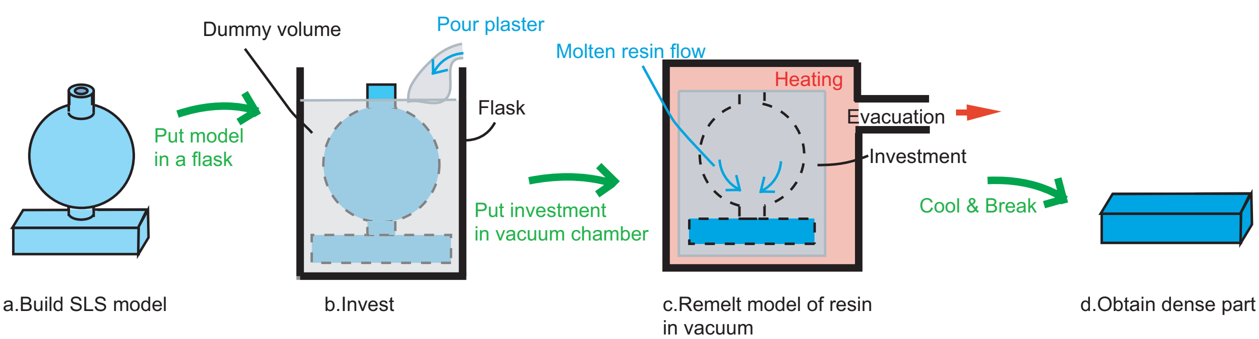


Fig. 1 Densification Process

Experiments

Heating and evacuating system

Fig. 2 depicts composition of heaters and vacuum system. The vacuum chamber is made from stainless steel and all the gasket is oxygen-free copper. Thus the chamber resists against high temperature above 300°C. Capacity of the chamber is approximately 9400cm^3 (9.4ℓ), and it is evacuated with a rotary pump of which evacuation rate is $1700\text{cm}^3/\text{s}$ ($100\ell/\text{minute}$). The chamber is equipped with two systems of thermocouple feedthroughs. The chamber is placed in an oven whose highest temperature is 270°C.

Heating temperature and time

Densification of parts out of CastForm PS was experimentally performed. To test the process, test pieces as shown in Fig. 3 were fabricated with Vanguard HS. The test piece consists of two sections, a cube and a sphere. The two sections are connected with a short cylinder, and the cube and the sphere are used as the desired shape and the dummy volume, respectively.

The most important parameters that affect successful densification are heating temperature and time for which the model is kept at the temperature. Higher temperature gives better liquidity to the molten resin, and longer heating improves replication of the shape. On the other hand, both of them encourage deterioration of the resin, and excessive temperature or heating time yellows the densified parts. Thus the temperature and time must be minimized.

To find the lowest temperature that can liquidify the resin and make it flow into the lower cavity, preliminary test was performed. One gram of the powder including small lump as shown in Fig. 4a is put in a oven, and time when powder of CastForm is measured. At 180°C, the powder melted and the surface becomes flat in 15minutes as shown in Fig. 4b. Contrarily, in case of 170°C, some lumps are still remaining even after 1hour, and the surface of the powder cannot become flat(Fig. 4c). Therefore, we defined the lowest temperature that liquidifys CastForm as 180°C.

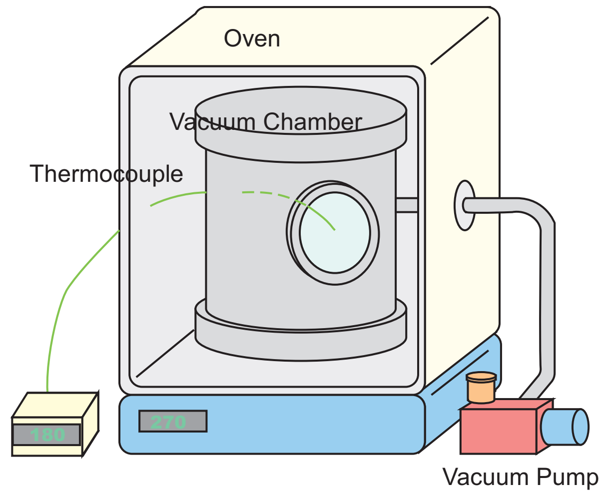


Fig. 2 Composition of Heating and Vacuum System

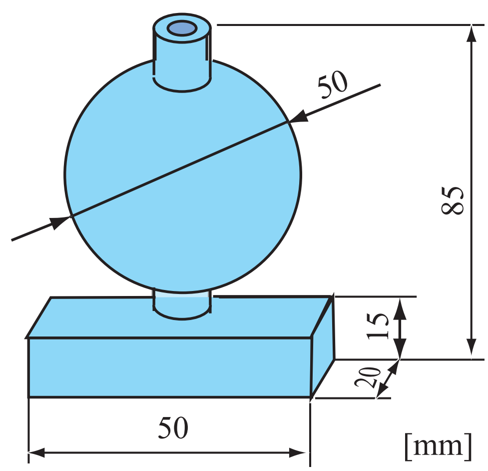
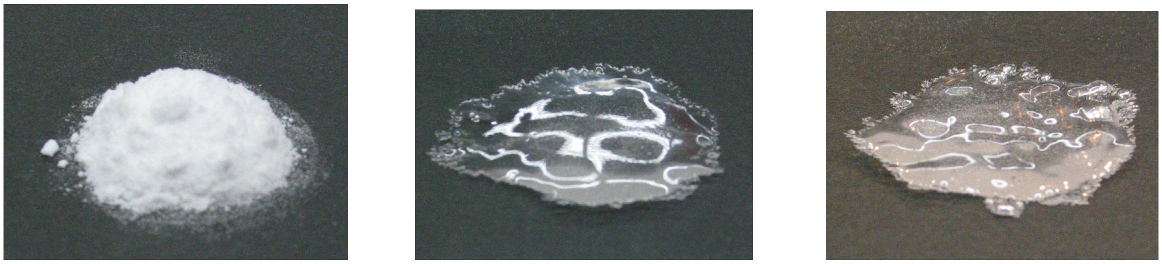


Fig. 3 Dimensions of the model used in densification test



a) Original powder b) after15 minutes at 180°C c) after 1 hour at 170°C

Fig. 4 Result of Preliminary Test to Find the Lowest Liquidifying Temperature

To find optimal heating time, four types of heating profiles (type A through D) were tested.

- **Type A**

After evacuating the chamber that was containing the investment, the thermostat of the oven was set at the lowest liquidifying temperature of 180°C. Fig. 5 displays variation of temperatures of the air in the oven, investment's surface and resin. As shown here, it took 10 hours for resin to reach 180°C. After that, another 3 hours was spent for full densification.

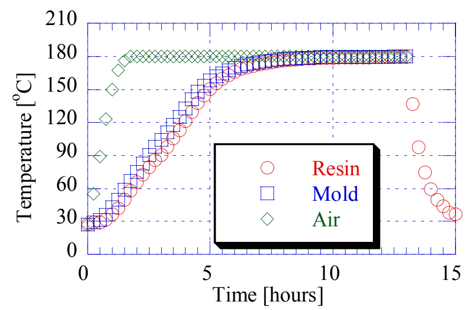


Fig. 5 Variation of temperature at each point in type A experiment.

As a result of this densification, the density of the parts increased from 0.371g/cm^3 to 1.051g/cm^3 reaching typical value of polystyrene. In the obtained part, no hollow whose diameter is larger than 1mm was observed. However, microscopically small bubbles are remained.

- **Type B**

A higher temperature of 270°C, which is the maximum of the oven, was tested. As shown in Fig. 6, it took also 10 hours to reach 270°C. After reaching 270°C, heater was turned off and the chamber was cooled down with the oven's door opened. Until the temperature of the resin downed to 180°C, inside of the chamber was kept vacuum to prevent the resin from deterioration or yellowing. After 1.5 hours, the temperature of the resin lowered to 180°C. Then, the chamber was vented and the investment was picked out. In this experiment, full densification had completed without keeping resin temperature at 270°C for a certain period because the resin's temperature have been higher than 180°C for more than 6 hours.

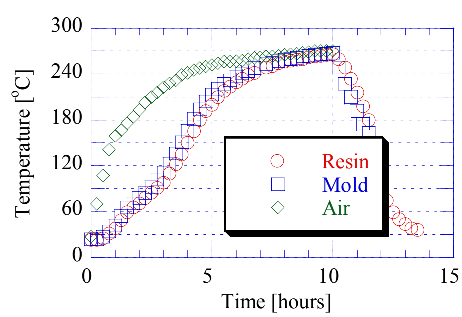


Fig. 6 Variation of temperature at each point in type B experiment.

- **Type C**

To minimize the required time for reaching 180°C, oven's temperature was set at the highest of 270°C until the resin temperature reached 180°C. After it reached, the vacuum chamber's surface was cooled down to 180°C rapidly by turning off the heaters and opening the oven's door to keep the resin temperature at 180°C. Then, thermostat was set at 180°C. As a result, the resin temperature was controlled as shown in Fig. 7. Afterward, by keeping resin temperature at 180°C for 4 hours, the part was fully densified, compressing the total densifying time to 9 hours without heating up the resin above 180°C.

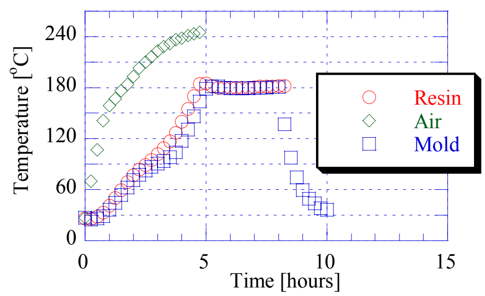


Fig. 7 Variation of temperature at each point in type C experiment.

- **Type D**

To reduce the total processing time more, following procedure was followed:

1. Start heating with the thermostat of the oven set at its maximum of 270°C
2. Heat the resin up to an adequate temperature above 180°C
3. Turn off the heater and open the oven's door to cool the resin down to 180°C
4. Pick the investment out of the vacuum chamber and break it when the temperature comes to 180°C

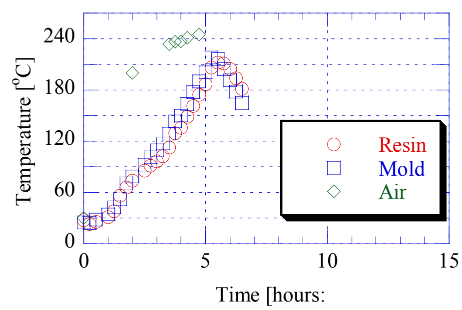


Fig. 8 Variation of temperature at each point in type D experiment.

By this procedure, the total process time was successfully reduced by 2.5 hours reaching 6.5 hours. Variation of the temperature in this experiment is displayed in Fig. 8. In this experiment resin temperature reached 212°C at maximum.

Deformation during densification

Difference in length at each point of the model as shown in Fig. 9 was measured as displayed in Tbl. I. In the densifying tests described in the previous section, two types of original pre-densified parts were used. The difference between these two types is only date when the models were built. There was no intentional difference in building parameters.

As for length ℓ and depth d, deformation caused by densification was very small as 1% or less. It is even

Tbl. I Deformation of each point after densification

Process	Original Part	Data Type	Point		
			ℓ	d	h
CAD Design	N/A	Length [mm]	50	20	15
Original part 1	N/A	Length [mm]	50.6	20.6	15.2
Original part 2	N/A	Length [mm]	50.4	20.1	15.1
Type A	1	Length [mm]	50.6	20.5	14.3
		Deviation [mm]	0.0	-0.1	-0.9
		Error Rate [%]	0.0	-0.5	-5.9
Type B	2	Length [mm]	52.0	22.1	15.8
		Deviation [mm]	1.6	2.0	0.7
		Error Rate [%]	3.2	10.0	4.6
Type C	2	Length [mm]	50.6	20.3	14.5
		Deviation [mm]	0.2	0.2	-0.6
		Error Rate [%]	0.4	1.0	-4.3
Type D	2	Length [mm]	50.6	20.3	14.7
		Deviation [mm]	0.2	0.2	-0.4
		Error Rate [%]	0.4	1.0	-2.6

smaller than that between CAD design and SLS parts. At the most point, length was increased. This seems to be caused by grains of plaster stuck on the parts. As shown in Fig. 10, a layer of plaster grain was stuck on the surface of the model. This plaster cannot be removed by plaster solvent, which is used in typical investment casting. Amount of stuck plaster tends to increase when process temperature is high.

With regard to height *h*, large decrease was observed. Shrinkage encouraged by absence of holding pressure seems to cause this decrease.

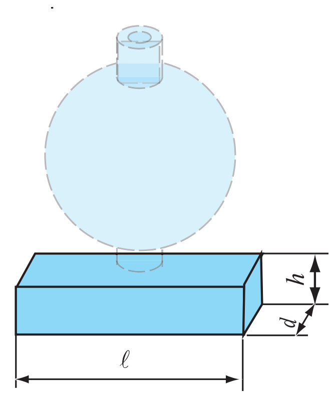
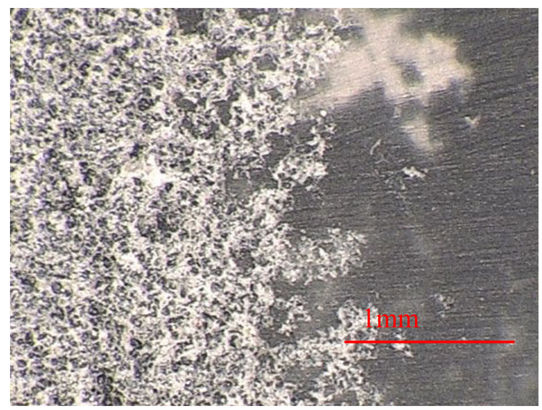


Fig. 9 Measured length

a) Plaster stuck on a model. (Partially removed)



b) Microscope photo of stuck plaster

Fig. 10 Plaster Stuck on a Densified Part

Tensile strength

Tensile rupture test was carried out on densified parts processed under various conditions, and their tensile strengths and Young's modulus were measured as listed in Tbl. II. As shown here, shorter process time at lower temperature prevents deterioration of the resin giving larger tensile strength and Young's modulus. The maximum strength of 13.5MPa was one third or quarter of that of typical injection-molded polystyrene.

Tbl. II Mechanical Property of Densified parts

Densification Condition		Tensile Strength	Young's Modulus
Temp.	Time		
180℃	4 hours	13.5MPa	759MPa
180℃	15 hours	9.4MPa	300MPa
270℃	15 hours	6.8MPa	188MPa

Light transmittance and color

Fig. 11 shows densified parts that are processed at 180°C for 11, 7 and 4 hours, respectively. After the process, each part was knocked out of its investment and machined into a cube of 10mm×10mm×45mm. As a result of full-densification, the parts became transparent since boundaries of refractive index, there used to be a lot of which between CastForm PS and the air, were eliminated. Light transmittances through paths of 5mm at wave length of 540nm were 63%, 53% and 59% respectively for the process times of 11, 7 and 4 hours.

The part that had been kept melted for 11 hours, model (a) in Fig. 11, appeared more yellow than the others to naked eye. However, there was no significant difference in light transmittance measurements at five wave lengths of 420, 460, 510, 540 and 600nm.

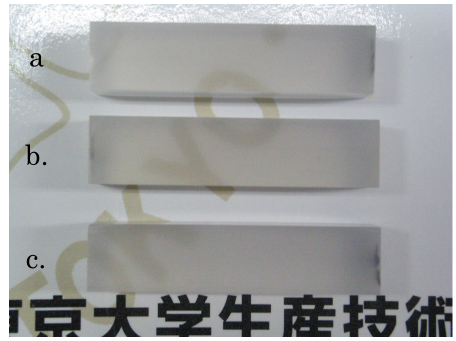


Fig. 11 Transparence of densified parts. Process times for parts a, b and c are 11, 7 and 4 hours, respectively.

Remaining bubbles

As mentioned in the previous section, no hollow was observed in densified parts. However, small bubbles, diameters of which could be measured as around 40μm were found as shown in Fig. 12. Each bubble seems to be containing thermal decomposition gas.

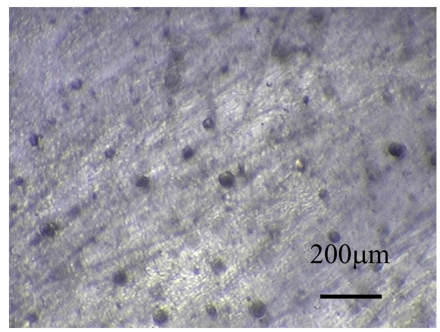


Fig. 12 Bubbles in the part

Discussion

As a problem, it took longer time for the investment loaded in the chamber to be heated up to the melt temperature than we expected. This is because of strong heat insulation of vacuum. In order to shorten this duration, heating system can be revised. For example, putting some heaters in the vacuum chamber and placing them near the investment or attaching them on the surface of the investment.

Since polystyrene is heated at high temperature for long period, the resin was deteriorated even if the circumstance was maintained vacuum. This deterioration weakened and yellowed the resin, and made small bubbles reducing transparency of the parts. To avoid this, the time keeping the resin at high temperature should be reduced. Pressurizing with inert gas such as argon after the resin is melted and pore network was blocked can be expected to enhance the replication speed. This can also reduce deformation caused by shrinkage.

Sticking plaster is very troublesome especially in densification of fine and complicated structure since finishing of which is difficult. There seems to be no easy solution, but using RTV as release agent was successful.

Conclusions

A process that can increase density of SLS processed porous parts to the material's original density remaining the shape of the model was introduced. The process was tested on densification of SLS parts out of polystyrene. Resultantly, it is found that the resin must be heated to 180°C at lowest and the temperature must be maintained for 4 hours at least. If the temperature is higher, the maintaining duration can be reduced. By this process, the density of the model was increased by a factor of 2.8. With regard to deformation during the densification, it is very small as 1% or less in horizontal direction. On the other hand, that in vertical direction is very large as 3 to 4% because of shrinkage. Tensile strength of the model was dramatically improved, but it did not reach that of material itself because of deterioration caused by high temperature during densification. Densification gave transparency, but the model was hazier and more yellow than injection molded polystyrene. The densified model did not include hollow inside but micro bubbles of which diameters are around 40μm.