Experimental Investigation into the Selective Laser Sintering of High-Impact Polystyrene

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ABSTRACT: High-impact polystyrene (HIPS) was used as selective laser sintering (SLS) material. The sintering parameters and the properties of sintered parts were investigated. The results show that sintered parts, which have good dimensional accuracy and good mechanical properties, can be fabricated with wide ranges of laser energy and bed temperature. To apply HIPS parts as functional parts, a reinforcement method, in which the sintered HIPS parts were postprocessed by infiltrating with epoxy resin, were suggested. The properties of the parts after postprocess were also studied. © 2008 Wiley Periodicals, Inc. J Appl Polym Sci 108: 535–540, 2008

Key words: selective laser sintering (SLS); high-impact polystyrene (HIPS); postprocess; epoxy resin; strength; mechanical property

INTRODUCTION

Selective laser sintering (SLS) is an advanced rapid prototyping technology, which applies a laser beam to create three-dimensional objects from powdered material. In the SLS process, illustrated schematically in Figure 1, a very thin layer of heat-fusible powdered material is delivered onto the movable platform by a roller. A heat-generating CO_2 laser beam traces across this layer, sintering specific areas according to the instructions of the computer-aided design (CAD) model. The platform lowers slightly and another thin layer of material is delivered. Then, the laser scans selected areas of this layer, which bonds to the previous layer. The process continues, layer by layer. The sintered material forms the object, while the unsintered powder remains in place to support the structure and is cleaned away and recycled once the build is completed.[1]

Differing from conventional manufacturing processes, SLS is an additive process, and can shorten the design-manufacturing cycle, hence reducing the production cost and increasing the competitiveness.[2] Comparing with other rapid prototyping technologies, one of the main advantages associated with SLS is material versatility. The large variety of materials is gradually allowed to extend the field of applications, from simple visual prototyping to functional parts and tooling. The most important materials used in SLS are thermoplastics.[3] Crystalline polymers, like polyamide, have been used to produce functional parts, which have fully dense and good mechanical properties, by SLS,[4,5] but the shrinkage associated with crystallization makes it difficult to produce parts with good dimensional accuracy, and the process control is difficult because of the strict sintering condition. Normally, because of lower shrinkages, amorphous polymers can produce more accurate parts. Polycarbonate (PC) and polystyrene (PS) have been widely used as SLS materials for making models for design testing and patterns. It is found that PS with low thermal expansion is more suitable for creating parts for investment casting applications.[6–12] However, to make thin-wall parts or parts with delicate structure by SLS, PS is not suitable, because of the poor mechanical properties of PS SLS parts. In this work, high-impact polystyrene (HIPS), a polymer blend of PS toughened with polybutadiene rubber, was used as a SLS material to make parts with better mechanical properties as well as good dimensional accuracy. Furthermore, to apply HIPS parts as functional parts, a reinforcement method, in which the sintered HIPS parts were postprocessed, was also investigated.

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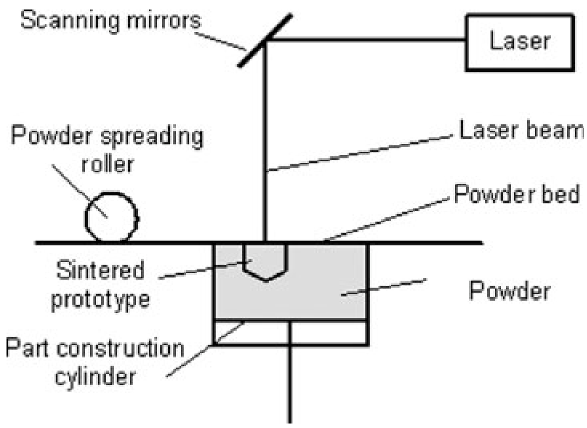

Figure 1 Schematic illustration of the selective laser sintering (SLS) process.

EXPERIMENTAL

Materials and instruments

1. Main materials: HIPS powders with a range of particle sizes from 75 to 100 μm.
2. Main instruments:

HRPS-III SLS system (equipped with 50 W CO_2 Laser), the Huazhong University of Science and Technology (HUST), People's Republic of China.

Electron universal testing machine, Model WDW-50, Shenzhen Kaiqiangli mechanical, People's Republic of China.

Impact Testing Machine, Model XCJ-500, Chengde Mechanical, People's Republic of China.

Scanning Electronic Microscope (SEM), Model LV JSM 5510, Japan.

Preparation of SLS specimens of HIPS

The HIPS powder was sintered on HRPS-III SLS system. The optimal sintering parameters were obtained by adjusting the applied laser power and the bed temperature. Those parameters were then used to sinter the specimens. The specimen for dimensional accuracy testing was shown in Figure 2. The tensile specimens were dumb-bell-shaped, and the dimensions were determined with reference to ISO527-2 Type 1A. The dimensions of flexural and impact specimens were 80 mm × 10 mm × 4 mm.

Postprocessing of specimens

The Bis-A diglycidyl ether type epoxy resins with different curing agents (epoxy resin system W and Y) were selected as reinforcing materials with which the HIPS SLS specimens were infiltrated. The infiltrated specimens were solidified for 6 h at 40°C, then 6 h at 60°C.

Measurement

Dimensional accuracy

The accuracy of SLS specimens is represented with the dimensional error S_1, which is defined as:

$$S_1 = [(A_1 - A_0)/A_0] \times 100\% \quad (1)$$

where A_0 is the design size given by computer, A_1 is the actual size measured by vernier caliper.

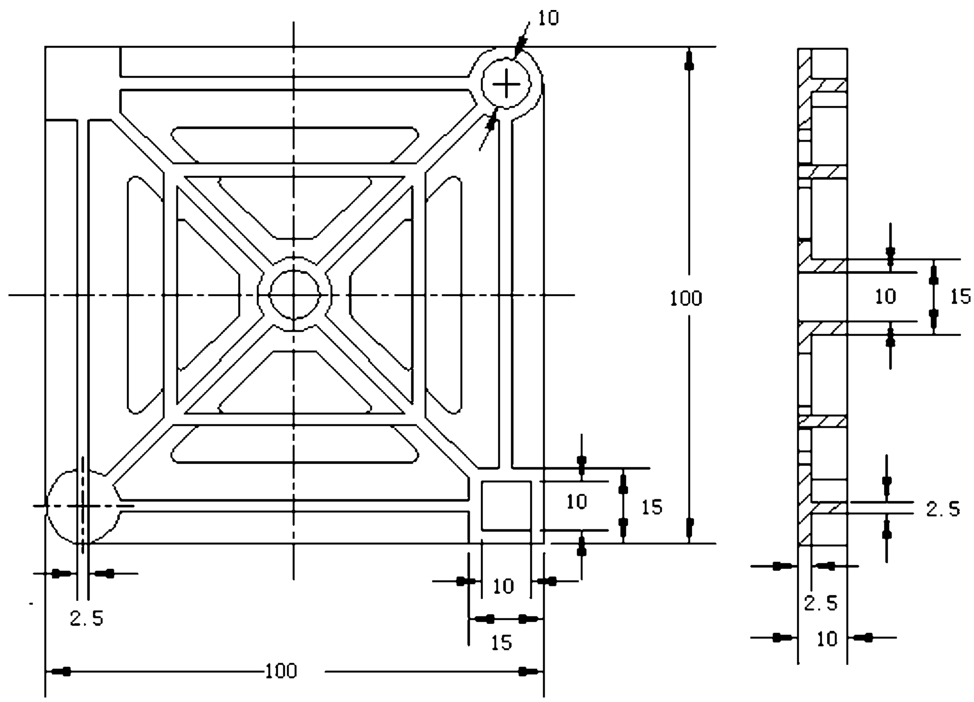

Figure 2 Standard specimen of SLS.

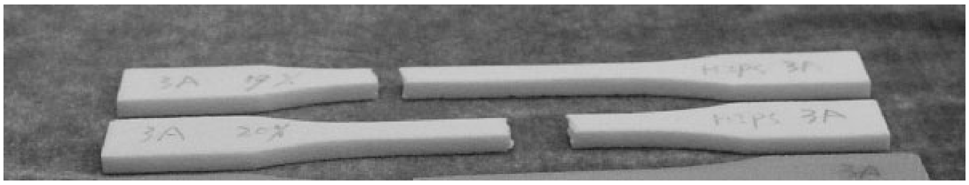

Figure 3 SLS parts of HIPS.

The accuracy of SLS specimens after postprocessing, S_2, is defined as:

$$S_2 = [(A_2 - A_1)/A_1] \times 100\% \quad (2)$$

where A_1 and A_2 are the sizes of SLS specimens before and after postprocessing, respectively.

Mechanical properties

The tensile, flexural, and impact properties of the SLS specimens were examined before and after postprocessing under ambient conditions. The tensile specimens were tested at a crosshead speed of 25 mm/min. The flexural specimens were tested at the speed of 2 mm/min. The Charpy impact properties were examined using unnotched specimens.

Morphologies and microstructure

The morphologies of the tensile-fractured surface were examined with scanning electron microscope at 30 kV voltage. The specimens were sputter coated with gold–palladium to avoid charging.

RESULTS AND DISCUSSION

Sintering parameters and specimens properties

Sintering parameters

Suitable parameters are essential for sintering process. Among those parameters, the powder bed temperature and the laser power have a great influence on SLS process. The powder bed temperature is the temperature to which the powder in the part cylinder will be preheated before the laser scanners move. A suitable bed temperature can reduce the laser power and the distortion during the sintering process. However, the powder bed temperature must not exceed the glass transition temperature (T_g) of HIPS, otherwise all the powder at bed surface could stick together. The laser power determines the amount of energy input to the surface of the powder by the laser beam. High laser power results in better consolidation of the HIPS particles and enables a more compact structure to be built (Fig. 3). When the laser power becomes excessively high, however, the resulting parts exhibit material degradation due to local overheating, and extensive growth due to heat diffusion beyond the part boundaries. The experimental results of different laser power and the powder bed temperature are shown in Tables I and II, respectively.

It is shown in Tables I and II that the ranges of laser energy and bed temperature for HIPS powder sintering are wide, and the specimens with good quality can be made under laser energy 13–14.5 W, bed temperature 90–95°C. In this article, the specimens were made with the parameters as shown in Table III.

The dimensional accuracy of HIPS specimens

The dimensional accuracy of HIPS specimens is measured and listed in Table IV. It is shown that the

TABLE I
Sintering Parameters of HIPS Powder—Laser Power

No.	Laser energy (W)	Tensile strength of SLS parts (MPa)	Remark
1	12	1.05	The specimens can be sintered, but the strength of specimens is poor.
2	13	3.82	The strength is suitable for investment casting applications.
3	14	4.59	The strength of parts is better.
4	14.5	4.78	The strength of parts is better, and the unsintered powder is easily cleaned away.
5	15	–	The unsintered powder is cleaned away difficulty.

Scanning spacing: 0.10 mm; scanning speed: 2000 mm/s; thickness of layer: 0.15 mm; powder bed temperature: 90°C.

TABLE II
Sintering Parameters of HIPS Powder: Powder Bed Temperature

No.	Bed temperature (°C)	Result
1	85	The part can be sintered, but has a little warp.
2	87	Successful part with flat surfaces (Fig. 3).
3	93	Successful part with flat surfaces and good accuracy.
4	95	Successful part with flat surfaces and good accuracy.
5	98	The powder surrounding the part agglomerates slightly during sintering.

Scanning spacing: 0.10 mm; scanning speed: 2000 mm/s; thickness of layer: 0.15 mm; laser power: 14 W.

TABLE III
Sintering Parameters of HIPS Specimens

Laser energy	14 W
Scanning spacing	0.10 mm
Thickness of layer	0.15 mm
Scanning speed	2000 mm/s
Powder bed temperature	90–95°C

TABLE IV
Dimensional Accuracy of HIPS Specimens

		A_0 (mm)	S_1 (%)
Length of side	X	100	1.23
	Y	100	1.54
Width of rib	X	2.5	0.43
	Y	2.5	0.78
Thickness	Z	10	0.43
Circle at corner	R	10	1.45
Circle in center	R_1	10	1.57
	R_2	15	1.70
Square at corner (inner diameter)	X	10	0.74
	Y	10	0.83
Square at corner (external diameter)	X	15	0.44
	Y	15	0.68
Thickness of baseboard	Z	2.5	0.33

specimen has a good accuracy, less than 2% at each position.

Mechanical properties

The mechanical properties of specimens sintered with HIPS and PS powder are listed in Table V.

As can be seen from the Table V, the mechanical properties of HIPS parts are much better than that of PS parts. When compared with PS, the particle bonding of HIPS powder is easier because of the viscose flow of rubber in the powder. This makes the sintered HIPS specimens compact in microstructure, and results in higher mechanical properties than that of PS specimens.

Microstructure of tensile specimen fracture

Figure 4 shows the microstructure of the fractured section of the tensile specimens. It indicates that HIPS particles do not melt completely during SLS process, and the adjacent particles are sintered together only at contact points, and the individual particles can still be identified. A large number of voids can also be seen. Those voids result in that the mechanical properties of SLS part are much lower than those of the compression-molded specimens.

Postprocessing for reinforcement of HIPS SLS specimens

With suitable sintering parameters, HIPS SLS parts have much better mechanical properties than PS parts, and can meet the quality requirements for patterns of investment casting. However, the mechanical properties are not good enough for the application of functional parts, and further improvement is necessary. So, in this article, sintered HIPS parts are reinforced by postprocessing, infiltrating with epoxy resin.

Effect of postprocessing on dimensional accuracy

The dimensional accuracy of SLS HIPS parts after post-treatment by both curing systems W, Y is listed in Table VI. It is shown that the variety of dimensions of the specimens after postprocessing is small. The effect on the accuracy of the two types of resin curing systems has no obvious difference. The average shrinkage ratio is 0.66% for system W and 0.85% for system Y. The possible explanation is that epoxy resin has a feature of small shrinkage during curing.

TABLE V
Mechanical Properties of SLS Specimen

Materials	Tensile strength (MPa)	Ultimate elongation (%)	Young's modulus (MPa)	Flexural strength (MPa)	Flexural modulus (MPa)	Impact strength (kJ/m2)
HIPS	4.59	5.79	62.25	18.93	946.85	3.30
PS	1.57	5.03	9.42	1.87	–	1.82

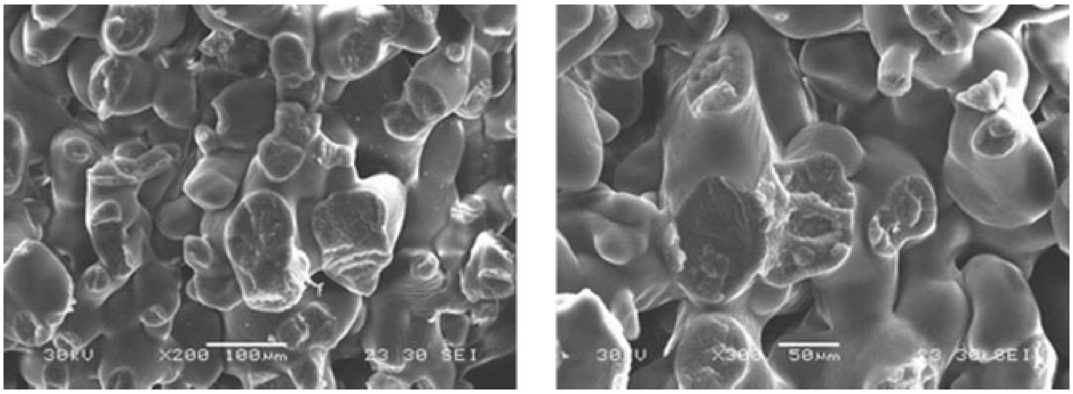

Figure 4 Electronic microscope photographs of the HIPS samples.

The effect of postprocessing on mechanical properties

Table VII shows the mechanical properties of HIPS SLS specimens after postprocessing by epoxy resins.

TABLE VI
Dimensional Accuracy of PC SLS Specimen After Postprocessing

		Epoxy resin system W	Epoxy resin system Y
		*S*2 (%)	*S*2 (%)
Length of side	X	0.98	1.12
	Y	1.00	1.15
Width of rib	X	0.65	1.08
	Y	0.47	0.89
Thickness	Z	0.97	0.90
Circle at corner	R	0.64	0.59
Circle in center	R1	0.38	1.04
	R2	0.41	0.58
Square at corner (inner diameter)	X	0.83	0.40
	Y	1.03	0.96
Square at corner (external diameter)	X	0.23	1.18
	Y	0.48	0.88
Thickness of baseboard	Z	0.49	0.31
Average *S*2 (%)		0.66	0.85

It is observed that the mechanical properties of specimen increase obviously after processing by epoxy resins, and the extent of reinforcement depends on the curing system of epoxy resins. When compared with the properties before postprocessing, the specimens treated by system Y increase by 315%, 62%, and 18%, respectively, in tensile, flexural, and impact strength; the others treated by system W increase by 257%, 35%, and 38%. Additionally, the system Y has a better reinforcement effect than system W in tensile and flexural strength, but the system W is better than system Y in impact strength.

Figure 5 is the SEM photograph of tensile-fractured surface after postprocessing. It shows that the voids among particles are filled with epoxy resin, and the epoxy resin becomes a continuous phase. HIPS SLS specimens become compact. Theoretically, when external force acts on the material, the resin

TABLE VII
Mechanical Properties of Reinforced SLS HIPS Parts

Curing system	Tensile strength (MPa)	Ultimate elongation (%)	Flexural strength (MPa)	Impact strength (kJ/m2)
Y	18.630	6.442	30.6863	3.90
W	16.020	6.848	25.5769	4.55

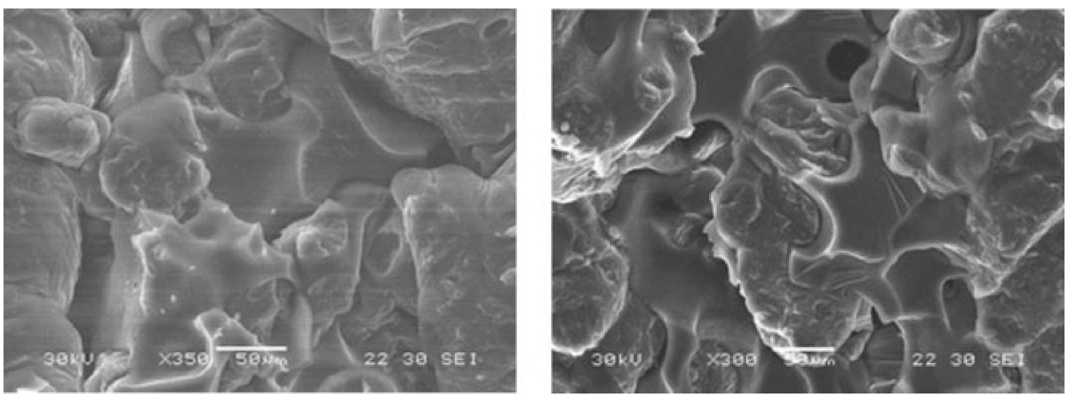

Figure 5 SEM of tensile fracture of SLS HIPS parts reinforced by epoxy resin.

will undertake most of the force. It reduces the destruction of the force on the contact points among particles, and results in a great improvement in mechanical properties.

CONCLUSIONS

HIPS can be used to produce SLS parts that have high dimensional accuracy and high mechanical properties in wide process conditions, laser energy 13–14.5 W, bed temperature 90–95°C, and is better than PS as a SLS material. After postprocessing by epoxy resins, the SLS parts of HIPS can be used for some functional parts because of the significant improvement in mechanical properties.

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