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# Rapid Manufacturing and Rapid Tooling of Polymer Miniaturized Parts Using Stereolithography

*Currently, miniaturization is a major trend in the manufacturing and commercialization of new industrial products. When small-sized objects should be manufactured with dimensions of only a few millimeters or less, many difficulties can appear using traditional processes. An alternative to study these new requirements is through the use of rapid prototyping technologies. Stereolithography (SL) has established itself as one of the most popular and reliable process allowing the rapid manufacturing of complex parts. This paper investigates the SL process, which directly produces small parts by rapid manufacturing, and also indirectly by rapid tooling. The processability of small parts was investigated using two different shapes. The POM and ABS materials were used in the indirect manufacturing. The dimensional accuracy, precision and tolerance of micro parts were evaluated using metrological techniques. Results showed accuracy and precision greater than 97% when small-parts are manufactured directly by Stereolithography*

**Keywords:** stereolithography, miniaturized parts, rapid tooling

## Introduction

In recent years the market for miniaturization has expanded, and many industries have produced parts with micro and small dimensions. This is due to the switch to modules in which the functions of several parts or subsystems are not handled by a single complex unit (Bertsch et al, 2000). This new generation of products has been characterized by the development of new manufacturing techniques, which generally possess different process conditions. When compared with traditional products, the end-application has shown similar requirements such as: mechanical properties, performance, and esthetic aspect. However, the small parts have their own specific requirements such as dimensional tolerance limits when compared with the traditional products class.

Regarding the high level of competition required by globalization, a short lead-time for prototypes and products has become a very important factor. Rapid manufacturing plays an important role in industrial development specifically through the techniques of stereolithography (SL) (Cavalheiro, Ahrens, Salmoria, 2006).

The SL process allows parts to be rapidly manufactured, layer-by layer, using the laser cure of a photosensitive resin. The main applications of the SL process are the rapid production of prototypes, models and molds for the automobile, electric, biomedical and aerospace areas. The thermal and mechanical properties are of great importance for rapid tooling, especially molds for the injection molding process, since these tools are subjected to working conditions, in which temperature and mechanical requirements vary through the time. The injection molding conditions and the part's shape can influence the thermo-mechanical and dimensional performance of the SL mold (Cavalheiro, Ahrens, Salmoria, 2006; Segal, Campbell, 2001; Ahrens, Beal, Ribeiro, 2003; Ribeiro, Hopkinson; Ahrens, 2004).

Therefore, current market demands and a new generation of products leads this work towards the strategic evaluation of the capacity of SL process to manufacture small parts directly and indirectly, analyzing the accuracy and precision of these processes

as well as dimensional tolerance in accordance with the international standard organization ISO 286-2 (1988).

## Material and Methods

The small parts evaluated were produced directly (Rapid Manufacturing) and indirectly (Rapid Tooling). The direct fabrication was conducted in a stereolithography machine SL-250/30A from 3D System and the indirect fabrication with an Arburg 320S 500/150 injection-molding machine.

The dimensional analysis was based upon statistic evaluation, in which the average represented the accuracy, precision was taken from the standard deviation and the tolerance was the difference between the maximum and minimum measurements.

### Selection of Shapes and Dimensions

The shapes and dimensions in the direct manufacturing were qualitatively defined on plates with square, circular and star shapes. The dimensions varied from 5mm to 1mm with hole's depth and pin's heights of 3mm. Figure 1 shows the SL plates with their respective shapes.

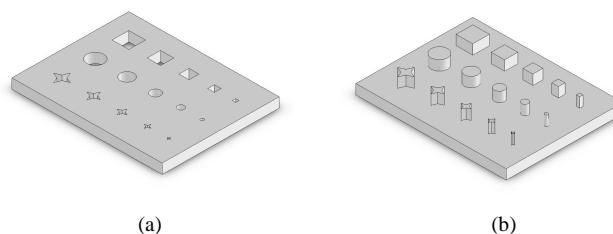


Figure 1. Shape and size test.

To ease the injection process the star shape was discharged against the selection of the square and circular shapes. The dimensions selected were 1.0 mm for direct and 2.0 mm for indirect manufacturing.

### Direct Manufacturing

To evaluate accuracy and precision in the direct manufacturing process plates with shapes and dimensions (defined in section 2.1) were used (Fig. 2). The epoxy resin Vantico SL5260 supplied by Huntsman was used as manufacturing material. With a layer thickness of 0.15 mm, the SL process was completed and the small parts were post cured by exposure to high intensity UV-light for 30 minutes.

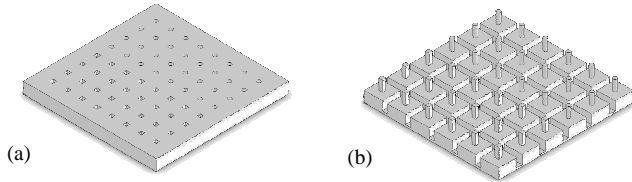


Figure 2. a) Plate shows shapes with holes b) Plate shows shapes with pins.

The measurement of the plates with holes were carried out using an optical microscope Leica DMLM by projecting transmitted light, and also an ESSS Imago 2.2 software, with a resolution of 1,639 $\mu$ m. The shapes were measured using the following procedure:

- Square shape – measurements were carried out in horizontal, vertical and diagonals directions.
- Circular shape – measurements were carried out at angles of 0° and 90°.

The plates with pins were measured using a micrometer Digimatic Micrometer model MDC-25PJ from Mitutoyo, with a resolution of 1  $\mu$ m. Both sides of the square shapes were measured.

### Indirect Manufacturing

The SL mold used to manufacture the small parts by rapid tooling was made by the “shell technique”. The same UV-treatment applied in the plates was used in the mold as well; afterwards it was back-filled with the epoxy resin (Huntsman RenCast CW 436). The SL mold shows 8 cavities in total: 4 in square and 4 in circular shapes. To help on the small parts ejection an insert system was coupled in the mold, as shown in Fig. 3. Figure 3a shows the mold together with the insert, while in Fig. 3b, the insert is being ejected. A total of three insert systems were produced.

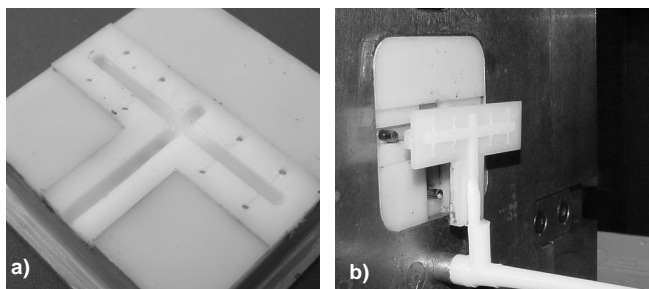


Figure 3. a) Mold and insert b) ejection of the insert cavity.

The Acrylonitrile Butadiene Styrene (ABS) M301AS supplied by Lustran and Polyoxymethylene (POM) M90 supplied by Celcon were the thermoplastics molded. The “short shot method” (Barry, et al, 1995) was applied to obtain the injection mold parameters. The parts produced were evaluated by the same evaluation criterion adopted to measure the parts produced by the SL process.

## Results and discussion

### Direct Manufacturing

A total of eight plates for direct fabrication process were manufactured, four plates with holes and four with pins. Figure 4 shows pins after its segmentation and the whole plate with holes.

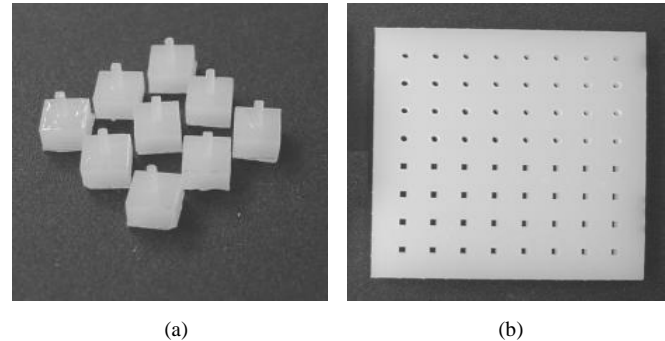


Figure 4. Segmented pins and plate with holes direct manufactured.

The measurements of holes dimensions are showed in Table 1. The overall accuracy (Eq.(1)) of the square holes evaluation was 97.33% for the edges and 98.60% for the diagonals. Regarding the individual evaluation of each plate, the edges' accuracy (Eq.(2)) ranged from 96.70% to 97.90% with a precision (Eq.(3)) range from 97.53 to 98.84%, while the diagonals' accuracy ranged from 98.23% to 99.65% with a precision range from 97.84% to 99.01%. The overall accuracy for holes with circular shapes was 98.15%. The individual evaluation showed an accuracy range from 97.10% to 99.90% with a precision range from 97.55% to 98.20%.

Overall accuracy =

$$[1 - (| \text{nominal value} - \text{mean value} |) / \text{nominal value}] * 100 \quad (1)$$

Accuracy =

$$[1 - (| \text{nominal value} - \text{average} |) / \text{nominal value}] * 100 \quad (1)$$

$$\text{Precision} = [(\text{average} - \text{standard deviation}) / \text{average}] * 100 \quad (1)$$

Table 1. Holes measurement data.

		Square holes		Circular holes
		Edges	Diagonals	Diameter
Plate 1	Average [mm]	1.030	1.389	1.021
	Standard Deviation	0.025	0.030	0.025
Plate2	Average [mm]	1.023	1.390	1.029
	Standard Deviation	0.015	0.028	0.022
Plate 3	Average [mm]	1.033	1.409	1.023
	Standard Deviation	0.012	0.014	0.020
Plate 4	Average [mm]	1.021	1.389	1.001
	Standard Deviation	0.017	0.019	0.018

The measurements done in pin plates are shown in Table 2. The overall accuracy of the square evaluation was 98.33% for the edges. The individual measurements for the edges accuracy ranged from 97.10% to 99.40% with a precision range from 97.28% to 98.11%. The overall accuracy for the circular shapes was 96.98%. The

individual evaluation showed an accuracy range from 95.40% to 98.50% with a precision range from 97.77% to 98.97%.

**Table 2. Pins measurement data.**

		Edges of square pins	Diameter of circular pins
Plate 1	Average [mm]	1.029	0.985
	Standard Deviation	0.028	0.022
Plate 2	Average [mm]	1.007	0.954
	Standard Deviation	0.024	0.011
Plate 3	Average [mm]	1.006	0.967
	Standard Deviation	0.019	0.012
Plate 4	Average [mm]	1.025	0.973
	Standard Deviation	0.020	0.010

The measurements show positive and negative tendencies. The accuracy reached a significant level with a dimensional deviation lower than 0.033mm for the square shapes and 0.046mm for the circular ones. The process also demonstrated a high precision level, with 68% of the measurements values showing accuracy above 96%. Otherwise, the dimensional tolerance measured in hole plates were 0.1mm for edges and 0.19mm for diagonals in square and 0.17mm for circular shapes. In the pin plates these were 0.1mm for the squares and 0.14mm for circular shapes. According to ISO 286 - 2 (1988), these dimensional tolerances are classified between IT 11 and IT 13 for fabricated dimensions. Knowing that, the final tolerance of the small parts should generally have IT classification within the range of IT 5 to IT 11, and ideally above IT 8.

The explanation for these errors relay on the fact that the SL process integrates many manufacturing processes as CAD/CAM, control of laser devices, materials, manufacturing parameter setup, and post-processing. Each of these individual processes can introduce errors that reduce RP product accuracy (Zhou, Herscovici, Chen, 2000). However, the process setup was able to produce the designed shapes with small parts dimensions.

**Indirect Manufacturing**

During the fabrication phase nine injection cycles were conducted for each insert using POM and ABS materials. The production in the inserts was alternated. The injection parameters used are shown in Table 3. These were calibrated during the first shots looking for the maximum quality of the small parts.

**Table 3. Process parameters used during injection molding.**

Parameters	POM	ABS
Nozzle Temperature [°C]	195	240
Injection Speed [mm/s]	90	110
Injection Pressure [Bar]	200	300
Cooling Time Before Ejection [s]	20	25

Table 4 shows the evaluation results of the parts dimensions manufactured in the SL inserts. The POM material shows an overall accuracy of 99.90%, while an accuracy of 96.10% for the circular shapes resulted. The ABS material shows an overall accuracy of 99.92% for square shape while an accuracy of 95.83% for the circular shapes resulted.

**Table 4. Injection mold measurement data.**

Inserts	POM		ABS		
	Square part Edge	Circular part Diameter	Square part Edge	Circular part Diameter	
Insert 1	Average [mm]	2.030	1.902	2.012	1.899
	Standard Deviation	0.025	0.053	0.025	0.037
Insert 2	Average [mm]	2.005	1.933	2.004	1.929
	Standard Deviation	0.042	0.047	0.031	0.033
Insert 3	Average [mm]	1.971	1.931	1.989	1.922
	Standard Deviation	0.031	0.038	0.024	0.04

Individual evaluation in the small parts manufactured with POM showed an accuracy range from 98.50% to 99.75% with a precision range from 97.91% to 98.77% for square shapes. Accuracy ranged from 95.10% to 96.65% with a precision ranging from 97.21% to 98.036% for circular shapes. For the small parts manufactured with ABS accuracy ranged from 99.40% to 99.80% with precision ranging from 98.45% to 98.79% for square shapes. Accuracy ranged from 94.95% to 96.45% with precision ranging from 97.92% to 98.29% for circular shapes. The square shapes resulted in greater accuracy and precision than circular shapes, what can be related to the SL manufacturing limitations to produce the mold insert cavities.

The accuracy measured during the indirect process (rapid tooling) also showed positive and negative tendencies, however, with a lower precision resulted when compared with the direct fabrication process (rapid manufacturing). Previous researches (Segal; Campbell, 2001; Ahrens, Beal, Ribeiro, 2003; Ribeiro, Hopkinson; Ahrens, 2004; Zhou, Herscovici, Chen, 2000) have indicated that mold temperature, injection pressure, holding pressure and shrinkage are direct influence factors.

Figure 5 shows the dimensions of the small parts as function of the injection cycles. The dimensions of the small parts manufactured with POM were not affected by the injection cycles. On the other hand, the dimensions for the ABS small parts results were affected by the injection cycles, as the overall accuracy decreased.

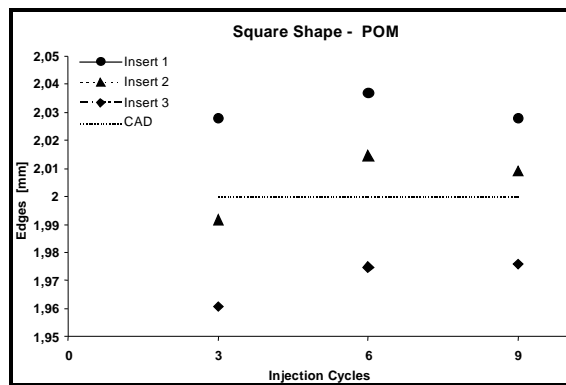
The dimensional tolerance measured for POM parts was 0.227mm for square shapes and 0.240mm for circular shapes. For ABS parts, these values were 0.151mm for square and 0.214mm for circulars ones. According to ISO 286-2 (1988), the range of the dimensional tolerances is classified between IT 13 and IT 14.

**Conclusions**

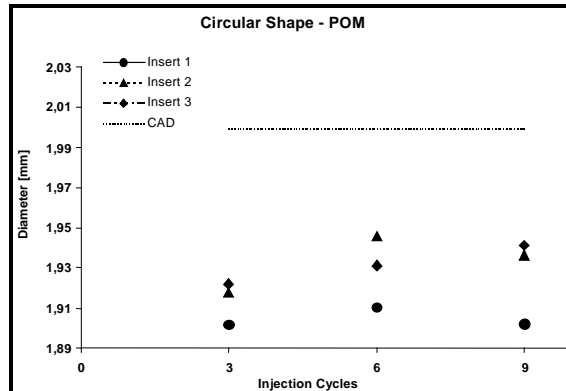
The accuracy and precision in the direct process presented values greater than 97%. However, for the application bore-shaft, important adjustments must be carried out to improve tolerance limits. The indirect process of fabrication also showed reasonable values in the aspects analyzed. The difference between the processes accuracy can be credited to the propagated error and difficulty to maintain stable the injection molding process when SL molds are used. This is because the material temperature, mold temperature, number of cycles and mechanical integrity of the SL mold influences the process.

Because the direct fabrication presented higher accuracy and precision than the indirect fabrication, the first one is more adequate for small parts manufacturing.

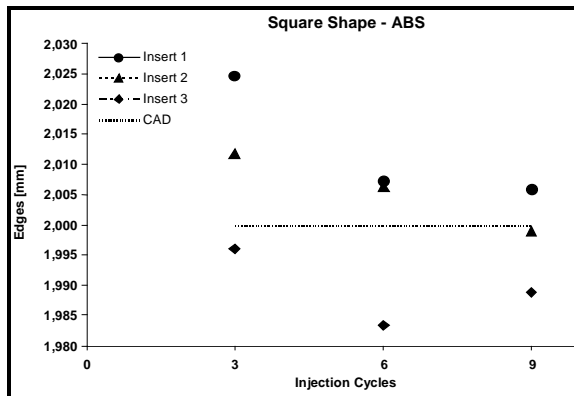
The Stereolithography technique seems to be a potential tool for miniaturization manufacture of shapes and dimensions like the ones used in this work.



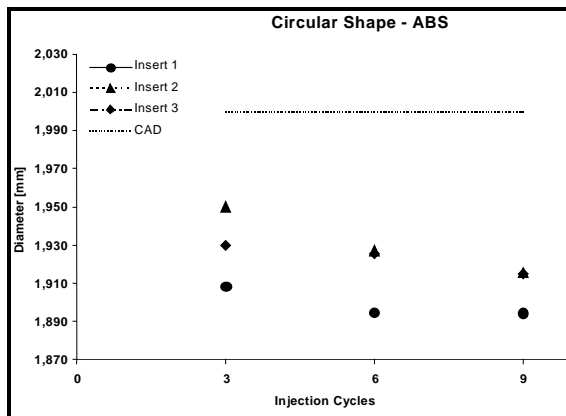
(a)



(b)



(c)



(d)

Figure 5. Dimensions of edges (b and d) and radius (a and c) for square and circular parts as function of injection molding cycles.

## Acknowledgement

The authors would like to acknowledge FAPESC, FINEP, CAPES and CNPq for the financial support.

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