The Use of Stereolithography Rapid Tools in the Manufacturing of Metal Powder Injection Molding Parts

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The utilization of stereolithography molds in the manufacture pre-series for injection molded plastic parts aims to reduce costs throughout the product life-time, but mainly during design and manufacturing phases. The use of this Rapid Tooling technique in powder metal injection molding is evaluated in this work. One of the greatest differences between traditional and stereolithography tools is related to the heat conductivity of the materials employed. For example, steel molds have a heat conductivity coefficient 300 times higher than molds made with the photosensitive resin used in the stereolithography process. The discrepancy regarding the cooling rate of the molded parts during the injection cycle must be compensated with adjustments in the injection molding parameters, such as temperature, pressure and speed. The optimization of these parameters made it possible to eject green parts from the mold without causing defects which would become evident in debinding and sintering stages. The dimensional analysis performed at the end of each case study showed that the shrinking factor of the component after the sintering had the same value obtained for components using traditional metallic molds. Moreover, the dimensional error remains under 2% which can be considered low for a pre-series of components (or prototype series).

***Keywords**: Rapid prototyping, rapid tooling, powder metallurgy, injection molding, stereolithography*

Introduction

In the competitive market, organizations have been using technologies that aid the achievement of rapid new product development with desirable quality and costs (Jacobs, 1992 & 1996). Considering complex geometric parts, two technologies deserve attention from the production sectors: Rapid Prototyping (RP) and injection molding. Rapid prototyping techniques are important due to their ability to reduce development time, to identify early errors in the project, to achieve a better communication within the project development team and to evaluate the functionality of the product along with many other benefits using physical prototypes/models. Others applications and evolutions from rapid prototyping are Rapid Tooling (RT) and Rapid Manufacturing (RM). In the case of rapid tooling, it is possible to build tools, such as molds, to produce pre-series of components by injection molding in a period shorter than one week. Stereolithography (SL) is one of the most versatile rapid prototyping techniques. This technology is capable of delivering fast and accurate 3D objects with a wide range of resins for many different uses (Wholers, 2001).

Powder Injection Molding (PIM) competes well with technologies such as casting, machining and forming when the components produced are small, complex and have tolerances within a narrow range. However, PIM has a high investment cost, because it needs an infrastructure with ovens, injection molding machines, a relatively expensive feedstock and a high accuracy mold, the latter two also influencing directly the final production cost of each component .[1]

Rapid tooling might possibly be used with powder injection molding to provide low-cost prototype molds. However, Hemrick et al (2001) and Gomide (2000) have described a particular behavior of PIM parts molded in SL tools. These authors affirm that irregularities in the mold surface have caused a strong attachment of the molded part to the mold. As a result the part broke in the mold opening and ejecting stages. Nevertheless, the injection molding parameters and mold design influence over the failures in the injection molding of mixtures of powder and binders were not completely described.

This paper describes case studies performed to evaluate the injection molding of stainless steel 316L metal powder in rapid molds produced by stereolithography. To clarify, a review about stereolithography with its rapid molds and powder injection molding is presented.

Stereolithography Tools for Injection Molding

Stereolithography is used to manufacture three-dimensional objects by means of photo polymerization of a resin by the energy delivered through an ultraviolet laser beam. A basic sketch of the process is shown in Fig. 1.

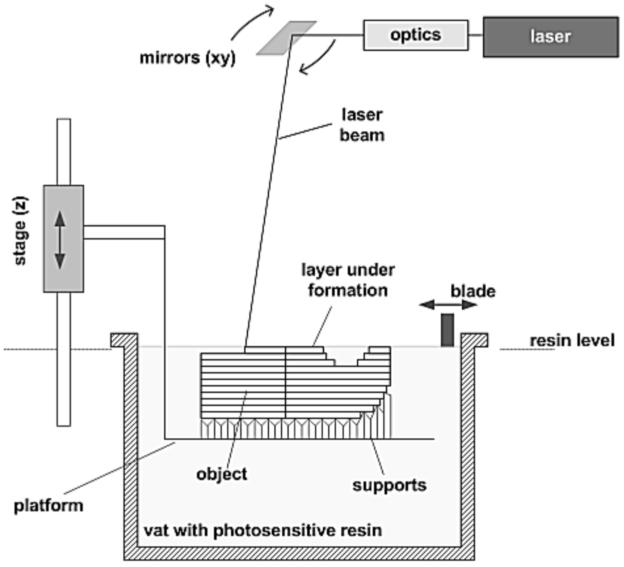

Figure 1. Sketch of the stereolithography process.

Basically, every rapid prototyping process starts with a CAD (Computer Aided Design) system. In the CAD, a three-dimensional

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object that represents the product is designed. The model is translated into a common language known as STL which is a triangular shell mesh of the object. This STL file is imported into the CAM (Computer Aided Manufacturing) of each process and is sliced into thin layers. Each layer represents one step of the process in the rapid prototyping machine. The CAM system also generates paths and manufacturing parameters according to the material and machine that is going to be used to build the prototype. Later, in the stereolithography machine, data from the CAM is loaded to commence the manufacturing process. The ultraviolet laser beam, as shown in the Fig. 1, is driven by galvanometric mirrors that scan the vat surface which contains a liquid photosensitive resin. The laser radiation activates a polymerization process and the resin hardens forming a solid layer of the three-dimensional object. After finishing one layer the platform dives and the liquid resin spreads over the solid layer. As the resin is too viscous, a blade passes through the surface of the liquid resin leaving a gap between the solid layer and the blade. The scanner starts to solidify a new layer attaching the new layer to the previously made layer. Layer-by-layer the object is manufactured by scanning selectively the laser beam over the resin surface. This short description is the original conception from 1988 developed by 3D Systems who developed the first RP commercial process. Furthermore, there are many variations in other stereolithography processes that use the photo-chemical principle to make and attach layers (Jacobs, 1996; 3D Systems, 1998).

This technology presents as an advantage its speed in manufacturing complex parts directly from the computer and it may be used in many different applications such as: prototypes for functional testing, bio-models for surgery planning, models for aerodynamic tests and rapid molds for injection molding. Using rapid molds, pre-series of parts are obtained in record time with the injection molding material chosen to manufacture the final parts. So, tests may be extended to a wide range of applications before expending time and effort on a definitive hard tool. This technology can be used to evaluate the mold analyzing its injection gates, ejection pins, split-lines, etc.

On the other hand, according to Dickens (1999), SL molds can mold from 20 to 500 parts of polypropylene which is considered very low compared to the worst metal molds that easily mold over 100.000 shots. The average life of the mold depends basically on the part complexity, injection molding material and procedures to set up the injection molding parameters in the injection molding machine. Most of the resins that are used to build SL molds have low mechanical properties above 70°C. Also the resins have low thermal conductivity (for example the SL resin DSM Somos 7110 k=0,2W/m.k). Thus, they are weak after they receive the thermal energy from the injection molded material that is injected usually above 180°C. When the mold is open and the part is ejected some features of the mold can break due to the ejection forces caused by the contraction of the part material over the mold cavity. To decrease early failures of the mold the injection molding parameters must be different from those used in metal molds. Figure 2 compares graphically the differences in their main parameters. Notice that the injection molding cycles are longer for SL molds due to their low thermal conductivity. As a result the injected material can show different mechanical properties caused mainly by different degrees of crystallization achieved (Segal & Campbell, 2001).

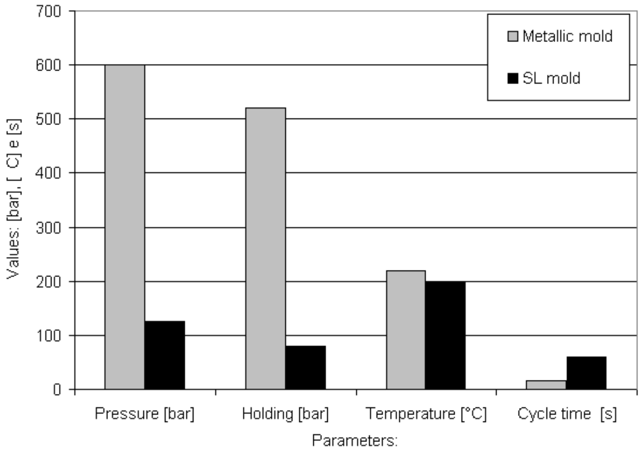

Figure 2. Graphical representation of typical values for polypropylene injection molding parameters for metallic and stereolithography molds.

Even though they present low mechanical properties, stereolithography molds can reproduce injection molding parts with fine details in less than 4 days without the high costs of a definitive tool (Gomide, 2000). Consequently it may aid engineering teams to evaluate their projects, avoiding error detection in later phases of new product development.

Powder Injection Molding

PIM technology is a combination of powder metallurgy with injection molding of thermoplastics. As a result it is possible to manufacture complex parts with metals, ceramics & composites. The hard particles of ceramics or metals are mixed with a binder system that covers the particles. This binder system is made usually of thermoplastic, wax and additives that allow the mixture to be molten and injected inside a mold in a way similar to that performed for thermoplastics alone. A basic sequence of the powder injection molding process is presented in Fig. 3.

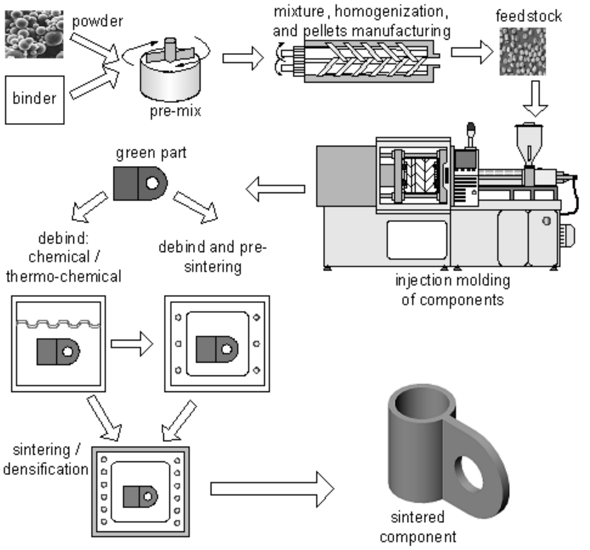

Figure 3. Sketch of the PIM process (adapted from German & Bose, 1997).

The process starts from choosing a combination of powder and binder system. The powder will be responsible for giving the proper mechanical, thermal, electrical and chemical properties to the manufactured part. The appropriate binder system will transport the particles to the inside of the mold and hold the shape, the part impression. After mixing, homogenizing and granulating the mixture it is placed in the feed system of the injection molding machine. The material is heated in the barrel by heater bands and shear caused by the rotation of the screw. After the material becomes molten it is injected inside the closed mold, applying a holding pressure to compensate the material contraction after it cools down. When the part is strong enough to be ejected the mold is opened and ejection pins extract the part from the mold obtaining a "green" part. The green part undergoes thermal and/or chemical processes of debinding to extract the binder system before the final thermal treatment to sinter the part. Sintering is responsible for achieving the optimal physical/chemical properties of the part material. The debinding and sintering treatments cause a 15-25% contraction in the part depending on the powder; binder, proportions and their applications. The process presented in Fig. 3 is a basic process but there are many variations in each step.

The use of powder injection molding may be employed for economical or technical reasons. In Figure 4 many examples of parts obtained by metal powder injection molding, with simple and complex geometries are presented. There is a wide range of applications for this technology and it may be used to produce parts for industries such as automotive, aerospace, consumer products, medical implants, computers, armaments and etc.

Figure 4. Examples of simple and complex geometries which can be produced by the PIM process (Oemsuppliers, 2001 & Pacifsintered, 2001) (Figures not in scale).

German & Bose (1997) mention as main advantages of this technology well designed and highly complex parts, low costs for large scale production, high precision and repeatability, a high diversity of materials with excellent properties (mechanical, chemical, etc).

Powder injection molding has appeared due to limitations in the conventional uniaxial compaction which does not allow efficient compaction of complex parts. With PIM it is possible to obtain parts with densities higher than 95% of the theoretical value homogenously distributed in the part (German & Bose, 1997).

Methodology

To evaluate the use of stereolithography tools to mold PIM parts two case studies were performed. The first case study was carried out to identify the process difficulties. A second case study, using a more complex geometry considered the results obtained from the first. Conclusions were then drawn to establish the positive and negative points of this application.

Design and Manufacturing of the SL Molds

For the first case study a geometry that can be considered simple in relation to the injection molding process was designed. The geometry was easy to mold and eject with constant thickness. For the second case study a more complex geometry was designed with a welding line caused by injection material flow around a core that made the ejection difficult. These geometries with the injection gate position and welding line are presented in Fig. 5.

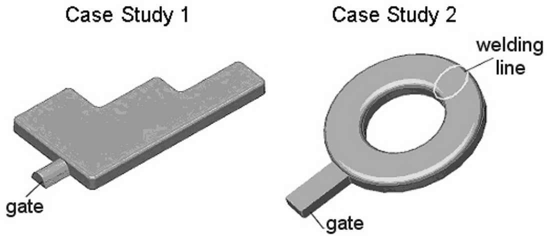

Figure 5. CAD models of the geometries used (See Fig. 9 & 10 for dimensions).

The dimensions of the case study 1 specimen were chosen without any concern for the final dimension of the parts obtained. The percentages of material contraction after the injection molding, after the debinding and after the sintering were therefore not incorporated into the CAD design. On the other hand, for the second case study the specimen was designed considering a volumetric contraction of 21,5% which is considered standard for the chosen material.

To design the mold for each case study, design guidelines for stereolithography molds (Gomide, 2000; Cedorge et al, 1999) and design rules for powder injection molding (German & Bose, 1997) were considered. To aid the ejection of the part from the mold ejector pins were distributed along the cavity surfaces. It is very important to homogeneously apply the ejection forces of the pins to the part surface because the green part is very weak even to handle. Also a draft angle of 1,5° was used in the first case study and 1° in the second. Both CAD mold designs can be observed in Figs. 6 and 7.

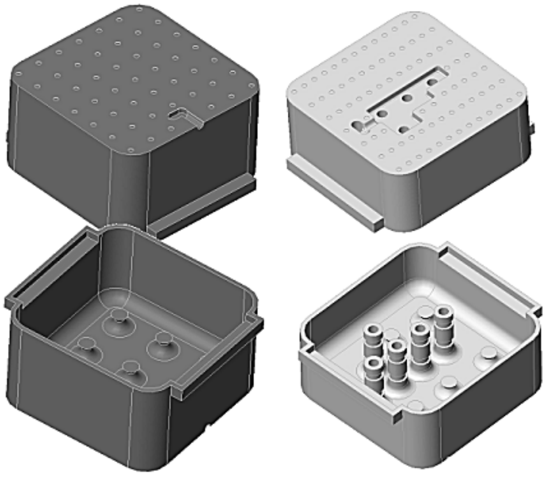

Figure 6. CAD mold halves for case study 1.

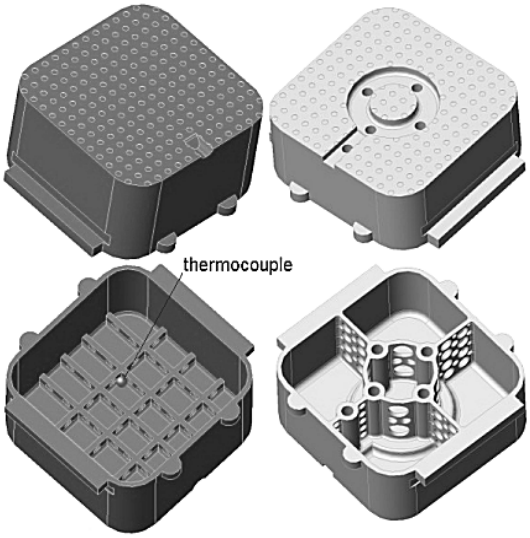

Figure 7. CAD mold halves for case study 2.

The molds were built in a stereolithography machine model SLA-250/30A with the resin DSM Somos 7110 using a standard building strategy with a layer thickness of 150µm. After building the molds they were cleaned with isopropyl alcohol and post cured inside an ultraviolet chamber for 1 hour. This procedure is standard for parts using this resin but it is possible to obtain extra cure with heat treatments. To avoid dimensional distortions no post finishing process was applied to the mold surfaces. As a result the staircase effect reported by Ahrens et al (2001) which is caused by the layer-by-layer manufacturing was reproduced in the molded parts. For economical reasons the molds as seen in Figs. 6 and 7 were designed in shell format. This approach saved resin and machine use hours. For this reason the molds needed a backfilling procedure to increase the mold strength. In case study 1 a polyester based resin (Massa Plástica Anjo) in-house filled with iron powder to diminish contraction was used. For the second case study an epoxy based resin with aluminum powder was used (Vantico Renshape RP 4036 resin & RP 1500 hardener – heat resistant casting system). To monitor the temperature, a K type thermocouple was placed in the back of the SL mold shell in this case study (Fig. 7). Figure 8 shows the mold of study 2 placed and adjusted in the bolsters ready for injection molding.

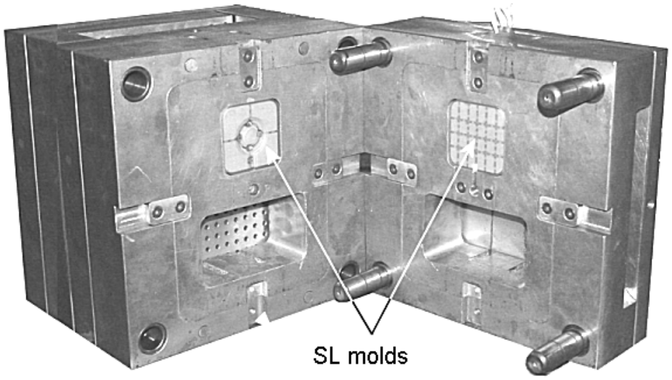

Figure 8. SL mold placed in the bolster.

The Injection Molding Procedures

Stainless steel 316L was used as the powder and the binder chosen to be used in the experiments was that presented in Table 1. The 316L was selected due to its economical importance indicated by German & Bose (1997).

Table 1. Mass percentage composition of the mixture.

Element	Mass %
316 L powder	91,50
Wax	3,47
Polypropylene	3,36
Vinyl Ethyl Acetate	1,40

Approximated values given by Steelinject 316L HMB1-91.3 Batch 260698-1 IR 000/98 (26/06/1998) ρ=4,73g/cm^3.

After assembling the bolster in the injection molding machine (Arburg Allrounder 320S 50T), procedures to adjust the injection molding parameters were taken.

For case study 1, the injection molding procedure started using safe parameters to avoid early failures to the stereolithography mold. This meant that low pressures, low clamping forces, low injection speeds, no holding pressures and lowest temperature to decrease viscosity of the feedstock were used. These parameters were changed gradually until successfully injection and extraction of parts from the mold without perceptible defects. Between each shot the impression was analyzed and a demolder (PVA, poly vinyl alcohol) was applied to the surface to reduce the ejection forces.

The parameters obtained from the first case study were used to indicate those for the second. Gradually the values were changed to make it possible to mold and eject parts considered good quality. After the 10th part obtained no demolder was used. To help the mold to cool down an air stream was used between each shot.

Debinding and Sintering Treatments

The best 19 parts obtained from case study 1 and 30 from case study 2 were debinded and sintered. The treatments were performed in the production line of Steelinject (Lupatech Industries Group). A description of the debinding and sintering is shown in Table 2.

Table 2. Description of debinding and sintering treatments.

Treatment		Parameters
Debinding (48 hours cycle)	Chemical debinding	Hexane vapor for 2 hours; Hexane immersion for 8 hours;
	Thermal debinding	H_2 + Ar Atmosphere; Final temperature 950°C;
Sintering (20 hours cycle)		Vacuum oven, H_2 + Ar atmosphere; 3 hours at 1300°C;

Measurement Procedures

Concerning the dimensional control, the dimensions from the molds before and after the injection molding were taken. The parts were measured after the molding and sintering. Figure 9 shows the dimensions designed in CAD for case study 1 where contraction was not considered. The same dimensions were measured on obtained parts.

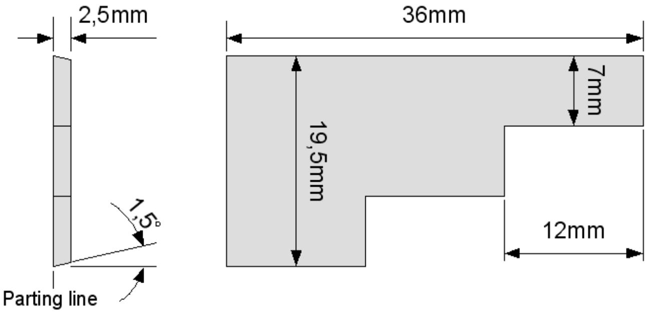

Figure 9. The cavity dimensions measured in case study 1.

Figure 10 presents the target dimensions for sintered parts and the dimensions measured in the mold for the case study 2. The parts chosen for measure were taken in cycles when the injection molding process was considered stable (after the initial adjustments) with constant time, speed and pressures. Also in case study 2, the mass of each measured part was taken after the molding and after the sintering treatment.

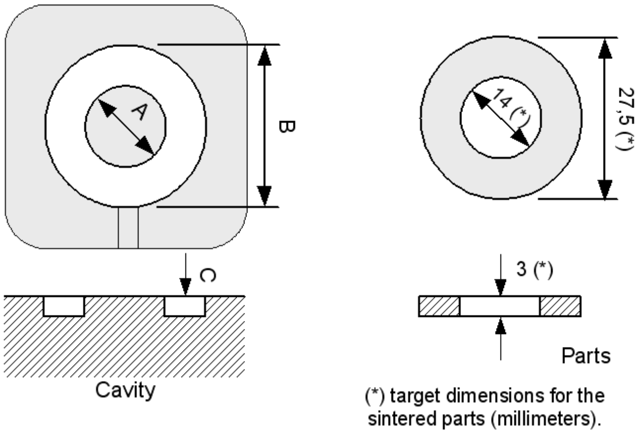

Figure 10. Dimensions measured in cavity and parts for case study 2.

Furthermore, as previously described, the temperature of the cavity was monitored using a K type thermocouple connected to a monitoring system (Picolog TC08, Picoteck Technology) with readings taken every 5 seconds.

Results

The parts obtained presented a good superficial quality after molding and sintering. Nevertheless, in case study 1 the incorrect adjustment of the ejection pins caused marks on the part that can be seen in Fig. 11. The parts obtained from case study 2 presented another defect. An excessive flash (thickness of 0,4mm) occurred due to the imprecise adjustment of the cavity closing. Later adjustments of the molds reduced the flash thickness to below 0,15mm. Figure 12 shows green and sintered parts obtained in case study 2 without flash.

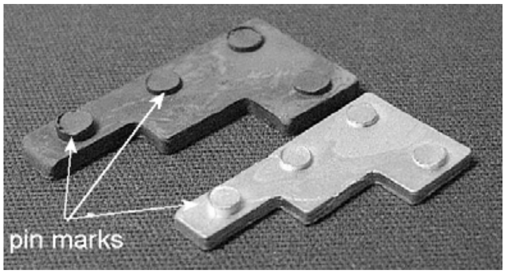

Figure 11. Pin marks on green (darkest) and sintered (silver) parts from case study 1.

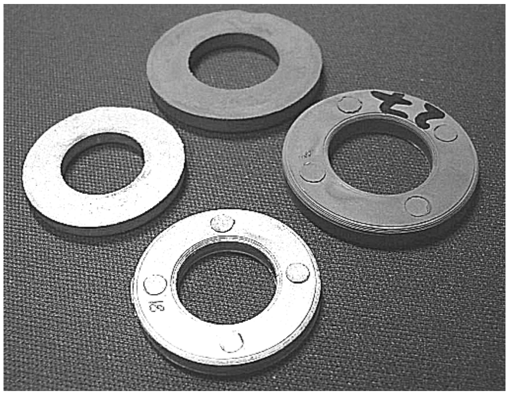

Figure 12. Parts obtained from case study 2: green (darkest) and sintered parts (silver).

Some of the most important injection molding parameters used to mold the parts in the case studies are presented in Table 3. The main divergences between the case studies are the holding pressures that were applied with more efficiency in case 2.

Table 3. Final injection molding parameters in both case studies.

Parameter	Units	Case study1	Case study2
Material temperature	[^{o}C]	190	190
Dosage material	[cc]	37,3	38,2
Injection speed	[mm/s]	70	110
Injection pressure	[bar]	390	382
First holding pressure	[bar]	65	210
Second holding pressure	[bar]	85	210
Cooling time	[s]	30	70

The cooling time measured in case study 2 was longer compared to case study 1. One of the main reasons for this was the stability of the injection molding cycles and the control of the temperature between each shot. Using the thermocouple it was possible to estimate better the right time to open the mold and to eject the part. The minimum time necessary to cool down the mold before starting another injection cycle was also precise. Figure 13 presents the monitoring results from the injection molding cycles for case study 2. The graph shows temperature variation over time for a thermocouple position of 0,5mm from cavity surface, pointing out the maximum temperature peak being 49^{o}C. Additionally, it was possible to obtain the total time for each cycle which ranged between 60 and 360 seconds due to the cleaning and cooling of the cavity.

The dimensions from case study 1 reveal that the percentage contraction of the parts after the sintering was 21,56%. This is a value close to the theoretical value, considering the measurement errors, for the mixture of powder and binder system used (refer to

Table 1). In Table 4 the dimensional percentage deviations compared with the CAD target dimensions for the final parts of case study 2 are presented. It can be observed that the mold dimensions change after the injection cycles. This occurs because the stereolithography resin is not completely cured after the standard building and post-processing procedures. During the injection cycles the combination of pressures and temperatures help to cure the resin but unfortunately change its shape. The final average results for the sintered parts present a discrepancy in dimension "C" which is related to the part thickness. This error is caused by the excessive flash mentioned previously which added an extra thickness to the parts. However, the results indicated that it is possible to optimize the mold design and finishing processes in order to overcome this problem.

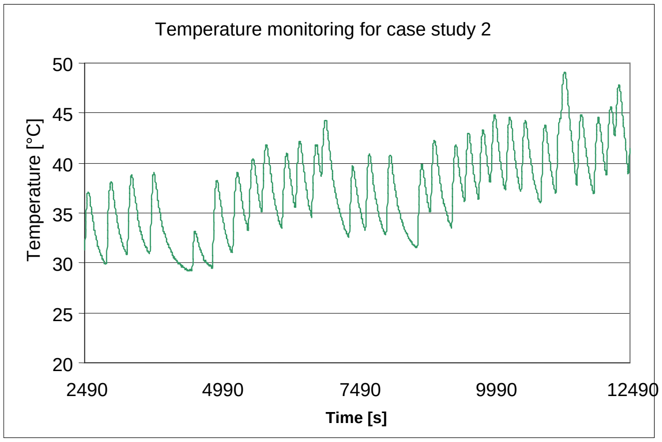

Figure 13. Monitored temperature in the mold for case study 2. Each peak represents an injection cycle.

Table 4. Dimensions of molds and parts compared with the target dimensions from the CAD design for case study 2.

	Mold before injections	Mold after injections	Average green parts	Average final parts
A (14mm)	17,03mm	17,47mm	17,22mm	14,23mm
Percentage deviation	+21,64%	+24,79%	+23,00%	**+1,64%**
B (27,5mm)	33,12mm	32,93mm	32,54mm	27,02mm
Percentage deviation	+20,44%	+19,75%	+18,31%	**-1,76%**
C (3mm)	3,82mm	3,72mm	4,00mm	3,33mm
Percentage deviation	+27,33%	+24,00%	+33,33%	**+11,00%**

A, B & C refer to Figure 10. CAD target dimensions in parenthesis. All values are averages with low standard deviation (max. 0,034).

Analyzing the mass variation of the parts it was possible to evaluate the pores percentage. Considering the CAD model for 100% dense stainless steel 316L and the mass average of the sintered parts the pore percentage was almost the same as those for parts molded in steel molds (3,65%).

Conclusions

Gomide (2000) & Hemrick et al (2001) affirm that the powder and binder system mixture sticks to the stereolithography molds causing difficulties in ejecting parts from the mold. Nevertheless, the adherence of the mixture to the cavity surface can not be completely explained by a single phenomenon. As in metallic molds, the injection molding process in SL molds presents many similarities although the values differ.

As in metallic molds, too high a holding pressure or too long a cooling period can make the ejection of parts difficult. They may cause the part to break or to crack. A well designed ejection system can diminish these problems. The holding pressures applied to injection molds made with the stereolithography resin are low due to the low mechanical properties of DSM Somos 7110 resin at high temperatures (Hopkinson et al, 2000). Ascertaining the correct cooling periods before opening and ejecting the part is therefore very crucial to the success of the process. A long cooling period leads to high contraction of the mixture (~1%) and it becomes too fragile to eject from the mold. If the mixture is not solid enough the part will deform in the mold opening. The injection and holding pressures are vital when injecting powder parts using stereolithography molds. Finding the correct pressure adjustments is a complex process because there is a minimum value to mold the part without defects and a maximum value that will not cause the part to excessively adhere to the mold cavities. It is also necessary to avoid pressures which are too high, in order to prevent early failure of the mold.

The superficial quality of the mold also plays an important role in the ejection of the part. In both cases studies no kind of surface treatment was applied. For the designed specimens this was not a problem because they were planar. However, for more complex parts it may be necessary to use techniques such as sanding, polishing and electroplating to achieve better surface qualities. It is also important to note that the machine used had a building resolution of 150µm and in new models it is possible to build 20µm layers giving a better surface quality and higher precision.

The injection speed used in the evaluated geometries was equal to those recommended for metallic molds (German & Bose, 1997 e Haupt & Walcher, 1998). The speed can not be too high otherwise it will cause flow jetting. Low speeds would not cause problems because the resin works as an insulator and it is unlikely that flow freezing would occur. When injection pressures are too low it is necessary to compensate with higher injection speeds.

The results obtained from the dimensional analysis, especially from the second case study, have proven satisfactory. Excluding the dimension affected by the excessive flash the dimensional errors were under 1.7% when comparing the target dimension to the final sintered part. Many authors (Kulkarni, 1996; German & Bose, 1997) affirm that tolerances for the powder injection molding process must be close to ±0,3%. Nevertheless, David (1998) affirms that for industrial applications tolerances of ±1% are more realistic. Considering that the use of stereolithography molds is mainly for design evaluation purposes inaccuracies around 2% are acceptable. Moreover, there are new resins for stereolithography with excellent mechanical properties even at high temperatures. Also, there is a new ceramic filled resin specifically for building injection molds.

The time to obtain a mold for stereolithography can be considered the greatest advantage of its application. Table 5 shows the time expended to obtain 100 green parts in case study 2. It is important to note that to obtain the final sintered parts more than 68 hours are necessary to debind and to sinter them. This is inherent to the powder injection molding process.

Table 5. Time of each step of case study 2.

	Description:	Time [hours]
1	CAD mold design	4
2	CAM strategies definition	0,5
3	Mold building in the SL machine	16
4	Cleaning and post-cure	1,5
5	Backfilling with epoxy based-resin + Al	0,5
6	Curing period for the epoxy resin	12
7	Finishing and bolster adjustments	3,5
8	Ejectors pins adjustments	0,5
9	Bolster assembly in the injection molding machine	0,5
10	Injection molding parameters set-up	2
11	Injection of 100 green parts	7
	Final total time to obtain green parts	48

The time to build the molds was 16 hours, using a laser power of 13mW (over time HeCd lasers units lose their power). With a new laser power of 40mW it is possible to build the molds in 9 hours, in the same machine. Using new machines with a laser power of 200mW and a faster recoating system the time can be reduced to 3 hours.

The period necessary to cure the backfilling material is also relative because as with the rapid prototyping machine it can be performed at the end of the day to get the objects ready for the next morning.

This work proves that it is possible to obtain powder injection molded parts from stereolithography molds. Despite the low complexity of the specimens it is possible to gain important information relevant to performing injection molding of more complex parts.

Acknowledgements

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