Application of solid freeform fabrication processes for injection molding low production quantities: process parameters and ejection force requirements for SLS inserts

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Abstract

Studies are underway for the application of solid freeform fabrication processes for mold inserts to be used in thermoplastic injection molding of low quantities of parts. This work initially compares a laser sintered insert (LaserForm™ ST-100) with a steel insert. Models and experiments determine process parameters, including molding latitude, and ejection force requirements. Ejection force predictions are based on work by Menges, using values for elastic modulus determined from tensile tests at ejection temperatures. Similar studies are planned for stereolithography inserts (SL 5170).

Introduction

Manufacturers who currently build products in low volume, such as aerospace systems, can benefit from tools that will cost effectively produce low quantities of production parts. Injection molding, which is typically a very high volume process, requires significant decreases in tooling costs in order to make low quantity production feasible. The application of freeform fabrication techniques, such as laser sintering, to build injection mold inserts is one approach to reducing these tooling costs.

Injection molds for high production volumes are traditionally machined of steel, are very strong, and have good thermal properties. The material properties of tools built using solid freeform fabrication (SFF) vary from conventional molds (see Table 1) but still may be suitable for injection molding lower quantities of parts. SFF processes are also attractive because they can generate complex geometries as easily as simple ones, e.g., they can build mold shapes and cooling lines that are impossible to machine. Selective Laser Sintering (SLS®) is a good example of a SFF process that can be used for injection mold inserts for low production volumes.

Injection molding simulations and experiments will be run with thermoplastic materials, first using a machined steel mold insert and then using a SLS® insert (see Figure 1). The objective is to determine process parameters and ejection force requirements for the sintered insert and compare them to those for the steel insert. A modular injection mold having a steel Master Unit Die mold base will be used, the core and cavity of which can be removed and replaced with those of other materials. Machining allowances were included in the design of the inserts so that they can be machined to fit properly into the mold base. The chosen part for this research is a vented closed-end cylinder, similar to the plastic canisters used to store 35 mm photographic film (see Figure 2).

Table 1: Properties of steel and SFF mold materials.

Process	Mold Material	Density kg/m^3	Tensile Strength MPa	Hardness	Conductivity W/mC
Baseline [1]					
Machining	P-20 Mold Steel	7870	1080	30-35 RC	47.6 @ 204C
	H-13 Tool Steel	7800	1550	52 RC	25.1 @ 199C
Rapid Tooling Materials *					
3D Printing – Prometal	Bronze/infiltrant	8100	406	60 RB	7.35
Laser Sintering – 3D Systems	Steel, w/copper	3450	33.6	75 ShoreD	1.28 at 40C 0.92 at 150C
	S. Steel, w/bronze	7700	510	79 RB as machined	49 at 100C 56 at 200C
Laser Generating – LENS	S. Steel 316	8000 [2]	800	80 RB [2]	15 [2]
Plastic Casting – CIBA	Ceramic-filled Epoxy		64 (UFS)	91 ShoreD	
Stereolithography – 3D Sys	SL 5170 cured resin	1220	59	85 ShoreD	0.200

*From company literature

Figure 1: SLS® core and cavity insert made with LaserForm™ ST-100.

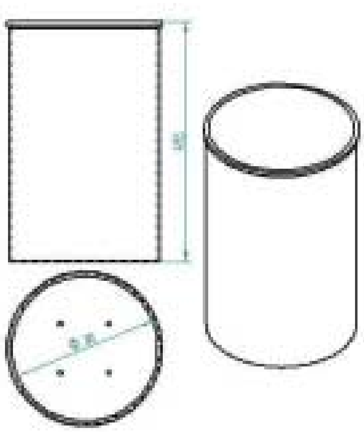

Figure 2: Canister part.

Theory

Process Parameters

A typical manufacturing environment in which very large quantities of injection molded thermoplastic parts are produced requires high quality products and minimal cycle times. Since viscosity of the thermoplastic melt decreases with increasing shear rate (see Figure 3), injection velocities are kept as high as possible to allow the mold to fill quickly and completely. Shorter cooling times are also favorable.

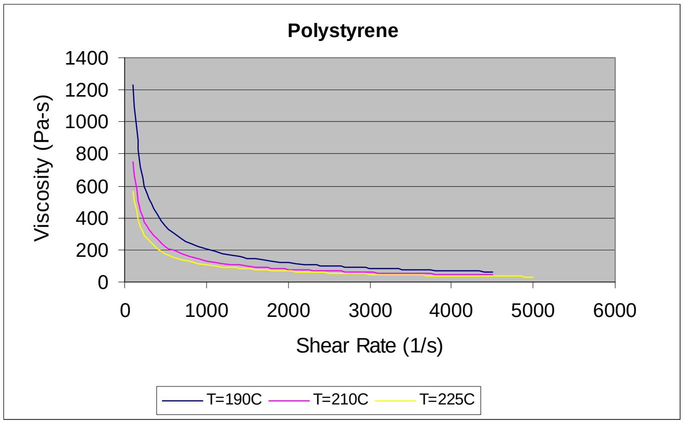

Figure 3: Viscosity vs. shear rate following the power-law model [3].

For the production of small quantities, part quality is still very important, but there is less emphasis on minimizing cycle times. If cycle times can be relaxed, then injection velocity may be decreased and cooling times may be increased. This allows for core and cavity inserts of different materials, such as SFF materials. Cores made with some SFF materials may not be able to withstand the pressures and temperatures used with steel molds. A balance must be found between velocity and viscosity, so that the polymer fills the mold completely and produces a quality part.

SLS® material LaserForm™ ST-100 has half the strength of mold steel, but comparable thermal conductivity. It is expected that injection velocity and temperature will have to be changed to some extent compared to those of the baseline steel insert. A simulation of injection force using a sintered ST-100 insert (Figure 4) shows that the core can withstand a reasonable injection velocity. At an injection pressure of 109 MPa, maximum deflection of the core at the point of injection is minimal (0.003 mm). For comparison purposes, a similar model is shown for a stereolithography SL5170 core. For the same injection pressure, deflection of the core is significant (0.3 mm).

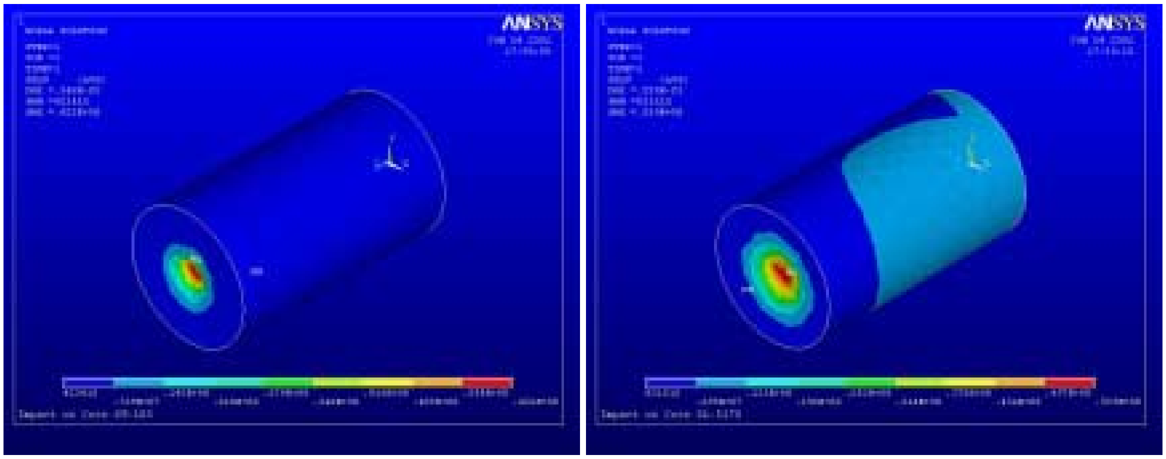

Figure 4: A simulation of stress due to injection pressure on an ST-100 core (left) and an SL5170 core (right).

Ejection Force

Ejection forces have two primary components: opening forces and, more importantly in this case, release forces. The mold material, the part material, and the processing conditions are all factors affecting release forces. For sleeve-type parts, the release force F_R can be computed from the coefficient of friction f, the contact pressure between the part and the core p_A, and the surface area of the core A_C, as follows [4].

$$F_R = f \times p_A \times A_C$$

For cylindrical sleeves, the part shrinks onto the core, and stresses are subsequently built up. Immediately upon ejection, the part recovers. According to Menges, the contact pressure can be estimated from the contraction of the part diameter or circumference. The relative change in diameter is given by

$$\Delta d_f = \Delta C_f = \frac{d_c - d_i(t_e)}{d_c}$$

where ΔC_f = relative change in circumference

d_c = core diameter

$d_i(t_e)$ = inside diameter of sleeve immediately after ejection.

Applying Hooke's Law,

$\sigma = E \times \varepsilon$

where σ = stress
E = elastic modulus
ε = strain.

Since, in this case,

$\varepsilon = \Delta d_f = \Delta C_f$

then

$\sigma = E(T_e) \times \Delta d_f$

where $E(T_e)$ = elastic modulus at ejection temperature.

Contact pressure for the sleeve is given by

$$p_A = \frac{\sigma \times s_m}{r_c} = \frac{E(T_e) \times \Delta d_f \times s_m}{r_c}$$

where s_m = wall thickness
r_c = core radius.

The surface area of the core is

$A_C = d_c \times \pi \times L$

where L = core length.

So, with the coefficient of friction, release force is

$$F_R = f \times \frac{E(T_e) \times \Delta d_f \times s_m}{r_c} \times d_c \times \pi \times L$$

Note that the coefficient of friction must be determined at process conditions during ejection, and modulus must be determined at ejection temperature. In this work modulus was measured by tensile testing polymer specimens at temperature, and ejection force will be measured experimentally using load cells behind the ejector pins. Coefficient of friction will then be determined using Menges' equation. Future release forces can therefore be calculated for these materials at these process conditions.

Methodology

SLS® Process

The laser sintering process used in this research involves a polymer-coated 420 stainless steel-based powder, known as LaserForm™ ST-100, and a 3D Systems Vanguard™ machine. Specifications of the Vanguard™ and material properties of ST-100 are shown in Tables 2 and 3.

When the 3-dimensional part is initially built on the Vanguard™ System, the laser heats the metallic particles above the glass transition temperature of the polymer coating. The polymer softens and deforms, then fuses with other particles at each contact surface. The temperature is such that melting of the metal does not occur, only viscous flow of the polymer coating. The metal powder is then bound together by the polymer to form the “green” part. After the build is complete, the green part is removed from the Sinterstation and excess powder is brushed away. A furnace cycle follows in a reducing atmosphere to burn off the polymer, sinter the steel powder, and infiltrate the part with bronze. Infiltration eliminates any voids within the steel, resulting in a fully dense part. [5][6]

Table 2: Vanguard™ System specifications (3D Systems).

Model Number	LC-100
Laser	DEOS CO2 Laser
Wavelength	10.6 microns
Power	100W max at part bed
Beam Diameter	450 microns
Max. Scan Speed	10,000 mm/sec (394 in/sec)
Min. Layer Thickness	(0.10 mm) 0.004 in
Build Chamber	381w x 330d x 457h mm (15w x 13d x 18h in)

Table 3: LaserForm™ ST-100 material properties (3D Systems).

Density	7.7 g/cm^3	ASTM D792
Thermal Conductivity	49 W/m^{o}K @100^{o}C	ASTM E457
	56 W/m^{o}K @200^{o}C	ASTM E457
CTE	12.4 ppm/^{o}C	ASTM E831
Tensile Yield Str. (0.2%)	305 MPa	ASTM E8
Tensile Strength	510 MPa	ASTM E8
Young’s Modulus	137 GPa	ASTM E8
Elongation	10%	ASTM E8
Compression Yld Str (0.2%)	317 MPa	ASTM E9
Hardness, Rockwell B	87 As infiltrated	ASTM E18
	79 As machined	ASTM E18

Modeling and Simulation

Mold fill simulations using MoldFlow® provide some validation of the mold design and predict what some of the processing parameters might be for the steel insert. These parameters are a starting point for experimentation and give a reference from which changes for other core materials may be determined. For example, Figure 5 shows the fill time for the canister with a HDPE melt temperature of 290^o C, a (steel insert) mold temperature of 104^o C, and an injection pressure of 123 MPa.

Simulations using ANSYS® are in process to determine contact pressures on the insert core and to predict required ejection forces, e.g., see Figure 6. The values for maximum contact pressure will be used with friction coefficient and surface area in the Menges equation to calculate required ejection force. Results of such simulations will be compared to experimental data, and a model of ejection force will subsequently be created.

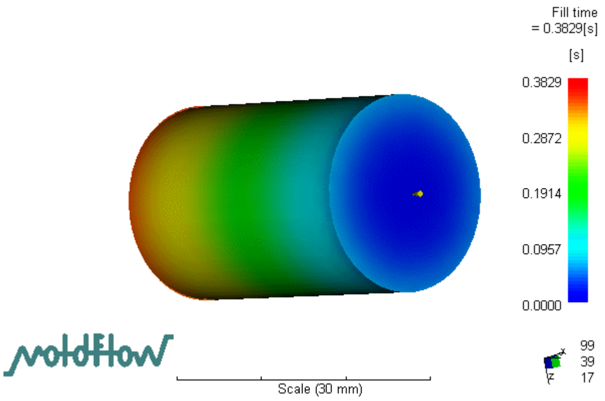

Figure 5: MoldFlow® image showing canister mold fill time for a steel insert.

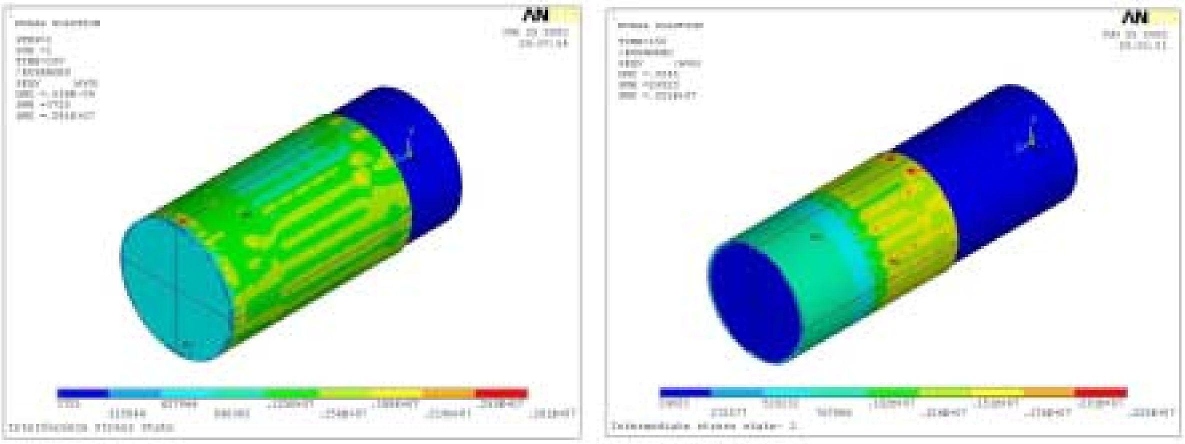

Figure 6: Contact pressure of the canister on a SL 5170 core prior to (left) and during (right) ejection.

Tensile Tests

Elastic moduli for high density polyethylene (HDPE) and high impact polystyrene (HIPS) used in this research were measured at various temperatures using ASTM D 638 “Standard Test Method for Tensile Properties of Plastics” as a guide. The testing apparatus was an Instron model 1322 tensile tester with a tube furnace. An extensometer with a 2-inch gauge and 50 percent strain was used to measure elongation.

ASTM Type I (dogbone) specimens of each thermoplastic material were pulled at room temperature and at ten degree increments, starting at 30^{o}C, until no elastic region was detected. HDPE was tested up through 70^{o}C, and HIPS was tested up through 60^{o}C. Results are shown in Figure 7. The values for elastic modulus will be used in ejection force calculations.

Experiments

Injection molding experiments will be run on a Sumitomo General Injection Molding Machine, model SH50M, a horizontal press with a fully hydraulic, 50-ton clamping system.

A series of injections with varying velocity and temperature will be run for each insert material to determine suitable processing windows. Values for the ejection force as measured by the load cells and canister diameter immediately after ejection will be recorded. Using Menges' ejection force equation and the elastic moduli described above, values for coefficient of friction will be determined for each core material, and the validity of the equation will be checked.

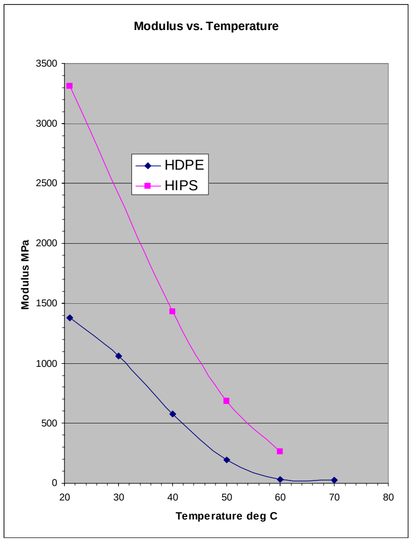

Figure 7: Modulus vs. Temperature for HDPE and HIPS.

Summary

If tooling costs can be greatly decreased, injection molding becomes a viable process for production of small quantities of parts. One approach to this is the use of SFF processes for making injection mold inserts. The research described in this paper will provide useful data on the feasibility of this rapid tooling approach. This work will give insight as to the changes in processing parameters that must occur and the ejection forces required to accommodate tooling inserts of different materials.

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