Thermal conditions in stereolithography injection mould tooling

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1. Abstract

The use of stereolithography (SL) as a rapid tooling technique for injection moulding provides a low cost and quick alternative to hard tooling methods when producing a small quantity of parts. However, previous work has shown that different characteristics are developed by crystalline plastic parts produced from SL moulds and those produced from conventional tooling methods. Differing characteristics means that the parts are not truly the same as those that would be produced by hard tooling and highlights a disadvantage to SL tooling.

Such differences are due to the cooling rate experienced by the part. Parts produced from SL moulds are cooled more slowly than those from metal tools as a result of the differing thermal conductivity of the mould material itself.

This work concerned establishing the extent of the difference in the heat transfer characteristics. The different cooling rates were demonstrated by real-time data acquisition. The results illustrated the very different thermal history imparted on the moulding that are likely to be the cause of characteristical differences in the parts.

The work then describes how the thermal conditions experienced in stereolithography moulds can be used to an advantage. A case study details the use of SL moulds for the injection moulding of polyether-ether-ketone (PEEK) which has high process parameter demands.

The results of the case study have shown that not only is the stereolithography rapid tooling method capable of producing a low volume of PEEK parts, but also under conditions that would not be possible using a metal mould. The thermal characteristics of stereolithography moulds allowed fully crystalline PEEK parts to be produced with the mould at room temperature; the equivalent steel mould would require a pre-moulding temperature of ~200°C and much higher injection pressures & speeds .

Keywords: Stereolithography, Rapid Tooling, Injection Moulding, Heat Transfer, Polyether-ether-ketone.

2. Background

The term Rapid Prototyping (RP) refers to the production of a physical geometry by one of a group of processes. RP processes directly produce a geometry from data derived from a 3D representation (i.e. CAD - computer aided design). The processes are characterized by generating the geometry by an additive, layer-by-layer manufacturing sequence, which when initiated runs unattended. Stereolithography (SL) is one such RP process. SL is the most mature commercial RP process, its development began in the mid 1980's. SL represents one of the most geometrically accurate commercial RP processes with a minimum feature size of approximately 0.1mm possible. SL generates a solid object by selectively curing a photosensitive liquid resin by exposure to UV light provided by laser. The part is generated section-by-section on a platform which is contained within the bath of the liquid resin. The materials that can be used in the process are restricted to acrylic and epoxy resins. Resins of very different characteristics are available but they are all essentially variants of epoxy and acrylic (in this work epoxy is used).

It has been shown that SL is capable of producing tooling cavities that can be used for the injection moulding of a limited number of parts in various polymers (1, 2, 3, 4, 5, 6, 7). The tooling cavities (inserts) generated by SL possess very different heat transfer characteristics as compared to traditional tooling materials for injection moulding:

<u>Thermal conductivity</u>

SL epoxy	0.2W/m-K
Steel	50W/m-K
Aluminium	200W/m-K

These differences in heat transfer properties have commonly been perceived as a weakness of the SL moulding process as they result in a slower cooling of the part and consequently longer production cycle times.

It has also been shown that the heat transfer properties of SL moulds results in parts that demonstrate different characteristics to those produced from metal moulds. Crystalline polymers have been shown to exhibit the following characteristics when produced from SL epoxy moulds as compared to those from metal moulds:

- Greater strength & stiffness (8)
- Lower impact strength (9)
- Greater density (10)
- Greater shrinkage (11)

Such differences relate to a higher level of crystallinity which is developed within the parts from SL moulds due to their slower rate of cooling. This slower rate of cooling is due to the difference in the thermal conductivities of the tooling materials.

This work illustrates the differences in the rate of part cooling in SL and aluminium moulds by a real-time data acquisition set-up. The advantages to the thermal conditions experienced in SL moulds is later demonstrated in a case study.

3. Methodology

3.1 Tool Design

The part and tool design used in the experiments were taken from earlier work in part shrinkage evaluation. The moulded specimen consisted of a bar shape with dimensions 12.7mm by 127mm, with a wall thickness of 3.2mm. This cavity was gated at one end, measuring 6.4mm in width and 3.2mm in depth. An open gate was utilised to ensure no areas of heat and pressure build-up, which SL moulds are vulnerable to.

The tool did not incorporate an ejection system in order to ensure a singular rate of heat transfer within the mould cavity, i.e. the inclusion of a steel ejector pin in an epoxy mould would provide an area within the mould that conducted heat at a greater rate. The absence of an ejection system was no problem as the parts were easily removed by hand.

The tool materials evaluated were SL epoxy and aluminium. Aluminium was chosen as suitable comparison metal tooling material as it is often utilised when producing metal tools in a short time (fast machining rates possible). Aluminium (AL) also represents a tool of highly contrasting heat transfer characteristics compared to SL epoxy.

3.2 Injection moulding

The polymer used in the injection moulding was Nylon PA66, specifically Bergamid A70NAT produced by PolyOne. This was dried immediately prior to moulding. The injection moulding machine used was a Battenfeld 600/125 CDC model with a Unilog 4000 control unit. This machine consisted of a 60 tonne hydraulic clamping unit and a 125x35mm reciprocating screw injection unit.

The defining injection moulding parameters were:

- The injection speed used was 100mm/second.
- The injection pressure was 150 bar.
- Upon mould filling a follow-up pressure of 150 bar was held for 1.5 seconds.
- A mould temperature of 23.5°C prior to injection and temperature recording.
- A melt temperature of 270°C.
- A cooling time of 40 seconds.

3.3 Temperature sensing

In order to establish the heat transfer characteristics occurring in each of the moulds, the temperature was recorded throughout the moulding cycle by the insertion of PTFE insulated k-type thermocouples with a welded tip. The thermocouples were inserted in three positions in the moulding cavity. Two were distributed evenly along the length of the moving side and one in the centre of the length on the non-moving side of the mould. These positions are illustrated in figure 1.

The tip of the thermocouple was situated such that it was located 0.5mm below the surface of the moulding face. The thermocouple was inserted from the rear of the mould insert through a 1mm drilled hole. The end point of the hole was created using a ball nosed cutter similar in profile to the welded tip of the thermocouple. This was created to ensure a good contact between the two surfaces without requiring any adhesives. It was thought that the use of any adhesives could create an inaccuracy in the recorded temperatures values due to the adhesive not having the same heat transfer characteristics as the mould material. Inserting the thermocouple firmly into the hole and securing with glue around the wire lengths enabled recordings to be taken without any signal disruption due to vibration from the injection moulding machine. The affixing of the thermocouples in the cavity inserts is illustrated in figure 2.

The tool temperature recording system was calibrated in order to verify that the recorded value from the thermocouple was an accurate reflection of the temperature condition at the mould cavity surface. After insertion in the mould, a known temperature was applied to each of the probe positions on the mould cavity surface and a comparison of the recorded temperature from each probe and the actual mould cavity surface temperature was made in respect to their simultaneous values and their response to temperature change. In both cases (SL & AL mould) the difference between the temperatures measured by the thermocouple and the actual surface temperature was never greater than +/- 1^{o}C.

The temperature profiles experienced in each mould were acquired by a data acquisition set-up that monitored and recorded the temperatures over a period of time. The readings were taken from the three thermocouples in each mould, these readings were converted to digital signals and, using a developed software programme, then filtered and sampled at linear intervals to provide a temperature history profile of the moulding conditions. This set-up recorded the temperature profiles experienced during the production of one moulding over a ten minute period. Twenty mouldings were produced and the temperature profiles recorded.

4. Results & Discussion

4.1 Temperature profiles during one shot

Examples of the thermal profiles experienced in the AL and SL moulds are shown in figure 3 & figure 4. The following observations can be made from the thermal history profiles:

- Each of the temperature profiles showed a consistent start temperature of ~23.5^{o}C. The temperature of the environment in which the injection moulding machine was situated was ~18^{o}C. The greater ambient temperature of the mould was caused by a combination of the closed cabinet (completely enclosed safety guarding) and heat from the machine's hydraulic clamping unit where the oil was maintained at a constant temperature.

- Close observation of the peak temperatures in each case shows that slightly higher temperatures are experienced by the probes closest to the gate where material enters the mould. This is probably due to their slightly longer period of exposure to the hot polymer melt due to the manner in which the mould fills.
- The SL moulds demonstrate a sudden drop after their temperature peak, at ~48-52 seconds. This was the time of mould opening when the heat in the mould suddenly finds another route to dissipate itself into the air. No such characteristic was displayed in the AL moulds as the temperature peaks after only 2.8 seconds and nearly all activity had ceased by 48-52 seconds

4.2 Average temperature profiles over twenty shots

The similarity between the thermal history profiles from each shot (no greater than +/- 5%) allowed an average temperature profile to be generated for each mould type (AL & SL).The average temperature profile experienced in each mould type over 20 shots is shown in figure 5.

The profiles shown figure 5 illustrate the vastly different temperature conditions experienced in the SL and AL moulds. The temperature activity in the AL moulds occurred in a very short period of time due to the materials high thermal conductivity. The temperature profile in the SL mould was more extreme and protracted, without external assistance (i.e. cooling by compressed air) the SL mould would take 15 minutes to return to its ambient temperature.

5. Case study

5.1 Background

The work described was conducted as part of the European Union funded IMS RPD project. The project partly involved research into the use of Stereolithography (SL) moulds for producing prototype quantities of plastic parts by injection moulding. The project had successfully moulded different polymers in SL moulds in an order that represented a progression in their difficulty. The polymers in chronological order were polypropylene, acrylonitrile-butadiene-styrene, polyamide 66 & polyamide 66 with 30% glass content.

The use of polyether-ether-ketone (PEEK) would represent a significant ‘jump’ in this progression to a highly mould-aggressive material. PEEK is a highly crystalline engineering polymer with great temperature resistance, great hardness, high accuracy, environmental stability and low frictional properties. It is used in top-end plastic applications such as in medical and aerospace industries. PEEK also has extreme injection moulding processing requirements; a melt temperature of 400°C, a mould temperature of approximately 200°C & a typical injection pressure of around 800 bar. This particular section of work was conducted in conjunction between the Rapid Manufacturing Research Group (RMRG) of Loughborough University and the global plastic processors, Ensinger in Germany.

5.2 First Trials

The first attempts at moulding PEEK in SL moulds utilised a simple mould geometry that had been used in previous experiments by the Author (12, 13). The mould consisted of a direct sprue which moulds around a central cylindrical core feature followed by a flange which the ejector pins act upon. A cross section of the mould is shown in figure 6.

Two of these SL moulds successfully produced 15 PEEK parts each. The moulds were in a reasonable condition after moulding, although they exhibited wear at the point of material entry into the SL moulds. The process parameters used are shown below:

Process parameters used in 1st trials

	Polymer melt temperature (°C)	Mould temperature (°C)	Injection pressure (bar)	Injection speed (mm/sec)
SL mould	400	23 (room temp)	25	7
Requirements in an equivalent steel mould (approx)	400	200	500	50

The parts themselves displayed very interesting characteristics. The part area in contact with the SL mould was grey, which indicated this area of the part was crystalline. The areas in contact with the steel sprue bush and ejector pins were brown, which indicated an amorphous region in the part. This is illustrated in figure 7.

5.3 Second Trials

The IMS RPD project utilised real part designs as a demonstration of technology transfer. An impeller provided by the industrial partner Rotax-Bombardier had been produced in various injection moulding polymers using SL moulds. After the initial success in the 1st trials it was decided that attempts should be made to produce these impeller parts in PEEK.

Two SL moulds successfully produced 10 PEEK parts each. The moulds suffered from wear at the first point of material entry into the mould and also at the 4 points of material entry into the cavity.

Process parameters used in 2nd trials

	Polymer melt temperature (^{o}C)	Mould temperature (^{o}C)	Injection pressure (bar)	Injection speed (mm/sec)
SL mould	400	23 (room temp)	30	10
Requirements in an equivalent steel mould (approx)	400	200	650	70

The parts again showed amorphous regions where the polymer came into contact with the steel areas of the mould cavity. These parts are shown in figure 8.

6. Discussion

The results have shown that the thermal characteristics imposed by SL moulds, which are commonly viewed as a disadvantage of the process, may in some cases be advantageous and allow moulding in conditions that would be unobtainable in metal tooling.

The success of the process and the characteristics of the part are due to the thermal properties of the mould. The great disparity in the thermal conditions experienced has been quantified by experimentation. The SL epoxy mould transfers heat away from the part much more slowly than the steel mould due to their different thermal conductivity. This allows for an unheated mould and lower process parameters to be used. This work illustrates the inherent heat transfer characteristics of SL moulds which enable their use in this injection moulding application, SL moulding would not be able to withstand the preheating and higher injection pressures and speeds that are required in equivalent metal tools.

It is particularly interesting that the mouldings exhibit amorphous areas where the polymer comes in to contact with areas of high heat conduction (the steel sprue bush and ejector pins). PEEK is a plastic of high crystallinity, which results in its favourable properties. The parts demonstrate that the development of high crystallinity would not be possible in an unheated steel tool, this why steel tooling must be preheated to ~200°C.

Presently even shorts runs of PEEK mouldings require Ensinger to produce a steel tool. Aluminium tools, which are faster to produce, are not a possibility as the heat conduction is even greater than steel and it would be very difficult to maintain the moulding faces at a temperature of 200°C.

7. Conclusions & Industrial Significance

• First known injection moulding of PEEK in soft tools.

• First known successful injection moulding of PEEK in unheated tools.

• Greatest known melt temperature used in SL moulding (highest previously used by RMRG; 270ºC).

• Demonstration of the lower process parameters that are possible with SL moulds due to their thermal characteristics.

• Demonstration of a possible alternative to steel tools for low volume production of PEEK parts at a greater speed and lower cost.

Word count: 2754

References

1. Hilton, P.D & Jacobs, P.F., 2000, *Rapid Tooling: Technologies and Industrial Applications,* (Marcel Dekker), ISBN 0-8247-8788-9.

2. Roberts, S.D. & Ilston, T.J., 1998, Direct rapid prototyping injection moulding tools, Proceedings of 7th European Conference on Rapid Prototyping & Manufacturing, July 7th – 9th, Aachen, Germany, Ed. by Campbell, R.I., pp 457-470.

3. Jacobs, P.F., 1996, Recent Advances in Rapid Tooling from Stereolithography, Proceedings of the 2nd National Conference on Rapid Prototyping and Tooling Research, 18th – 19th November, Buckinghamshire College, UK, pp 135 – 152, ISBN: 085298 982 2.

4. Stierlen, P. Dusel, K-H. & Eyerer, P., 1997, Materials for Rapid Tooling Technologies, 8th European Conference on RP&M. Nottingham. UK.

5. Dusel, K-H., 1997, Materials for Rapid Tooling Technologies, Society of Manufacturing Engineers Rapid Prototyping and Manufacturing conference, 22nd – 24th April, Dearborn, USA.

6. Luck, T., Baumann, F. & Baraldi, U., 1995, Comparison of downstream techniques for functional and technical prototypes- fast tooling with RP, Proceedings of 4th European RP Conference, 13th – 15th June, Belgriate, Italy, pp 247 – 260.

7. Schulthess, A., Steinmann, B. & Hofmann, M., 1996, Cibatool™ SL Epoxy Resins and Some New Applications, Proceedings of the 1996 North American Stereolithography Users Group Meeting, March 10 – 14, San Diego, USA.

8. Eschl, J., 1997, Experiences with photopolymer inserts for injection moulding, European Stereolithography Users Group meeting, 2nd – 5th November, Florence, Italy.

9. Dawson, K., 1998, The Effect of Rapid Tooling on Final Product Properties. Proceedings of North American Stereolithography Users Group Meeting, 1st – 5th March, San Antonio, USA.

10. Michaeli, W., Brinkmann, S. & Langen, M., 1996, How close are moulded parts from RT moulds to series production?, Kuntstoffe Plast Europe, v86, n11, November, pp 9-10.

11. Damle, M., Mehta, S., Malloy, R., McCarthy, S., 1998, Effect of Fibre Orientation on the Mechanical Properties of an Injection Molded part and a Stereolithography-Insert Molded Part, Proceedings of the society of plastics engineers (SPE) annual technical conference (ANTEC), Atlanta, USA, pp 584 - 588.

12. Harris, R. A., Newlyn, H. .A, and Dickens, P. M., 2002 [a], The Selection of Mould Design Variables in Direct Stereolithography Injection Mould Tooling, Journal of Engineering Manufacture, IMechE proceedings part B, Vol 216, No B4, ISSN 0954-4054. pp 499 – 505.

13. Harris. R.A, Hopkinson. N, Newlyn. H, Hague. R & Dickens, P.M., 2002 [b], Layer thickness and draft angle selection for stereolithography injection mould tooling, International Journal of Production Research, Volume 40, No 3, 15th February 2002, Pages 719 – 729, ISSN 0020-7543.

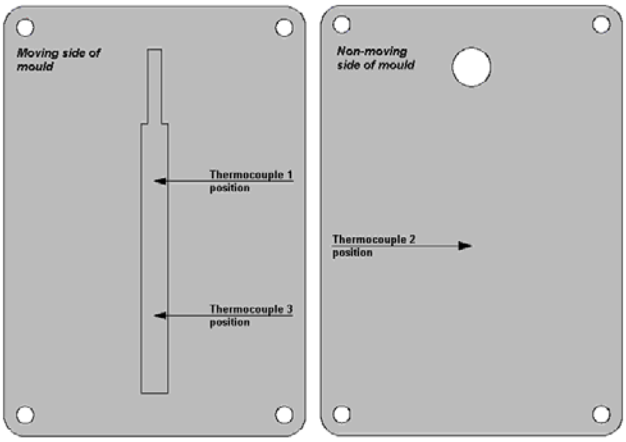

Figure 1. Probe position illustration

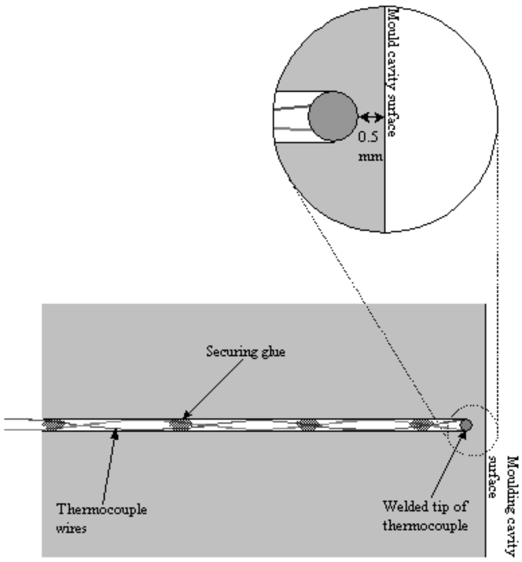

Figure 2. Cross sectional view of thermocouple insertion

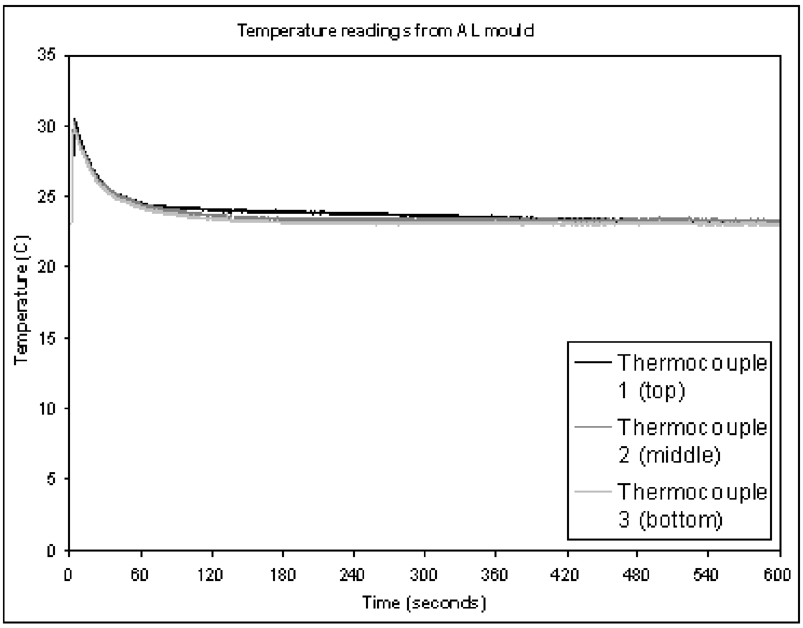

Figure 3. AL temp profile during 1 shot

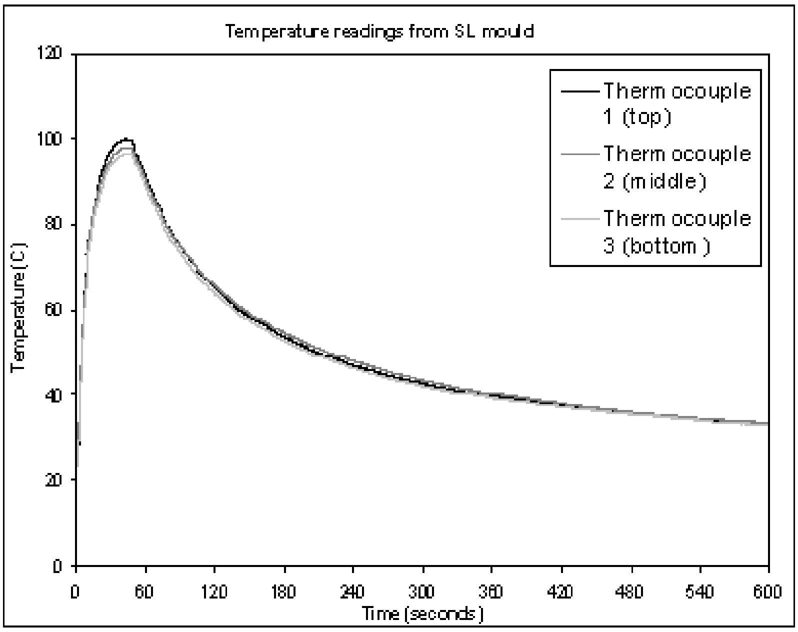

Figure 4. SL temp profile during 1 shot

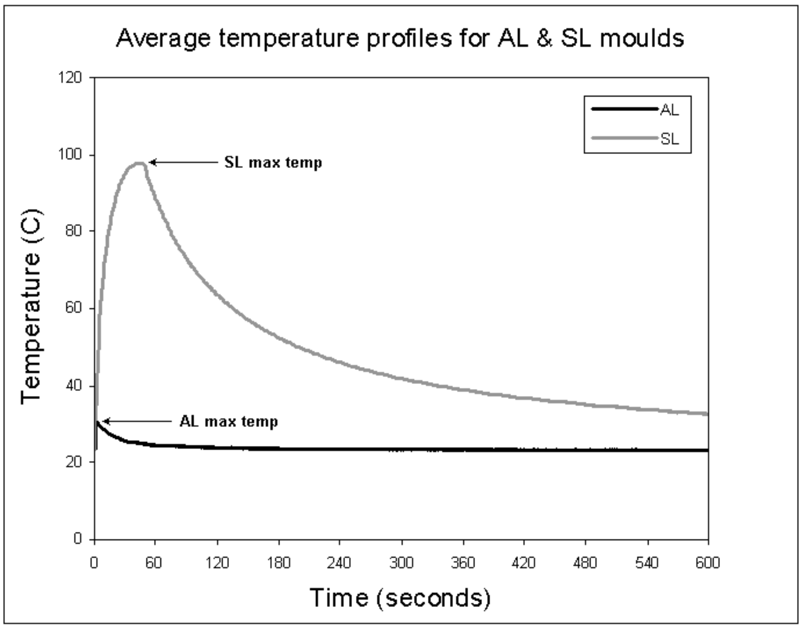

Figure 5. Average temp profiles for AL & SL moulds

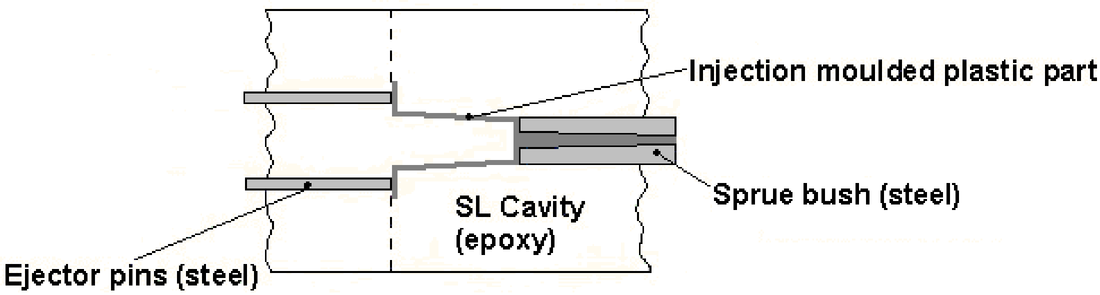

Figure 6. Cross section of 1st trial tool

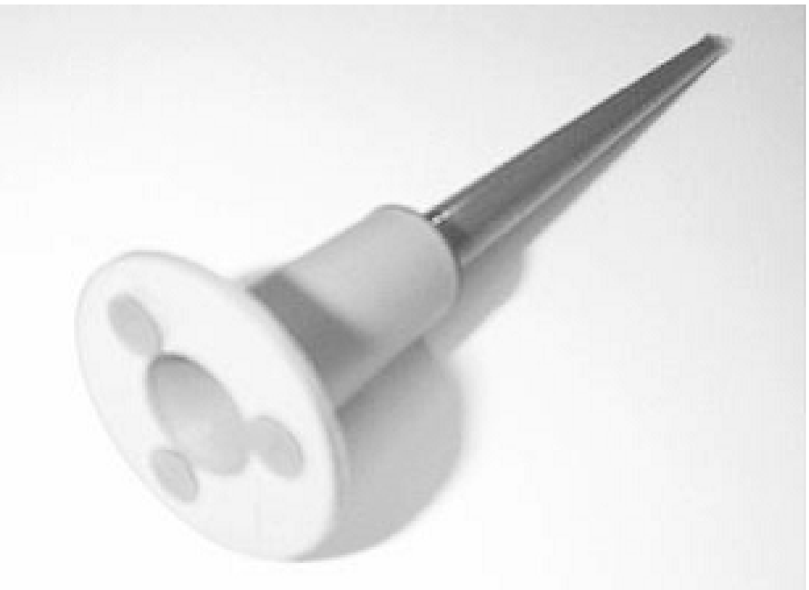

Figure 7. Part from 1st trials

Figure 8. Part from 2nd trials