Stereolithography Injection Mould Tool Failure Analysis

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1.0 Abstract

Manufacturing technology does not always enjoy the traditional cost benefits of mass production because large quantities may not be required. Separating low cost from high volume requires new approaches to product and process design and technology. Stereolithography tooling supports this concept by providing tools quickly during the design process to prove out and select optimal new concepts. The SL tooling technique is a first step in realising the near-term objectives such as conceptual modelling and design verification, as well as the long-term objectives in production.

At the University of Nottingham development of the SL injection moulding tools has taken place along two fronts. The first to provide material data for tool design under extreme conditions of stress and temperature; and obtaining data from different tests carried out on simple tools which resemble real situations (Rahmati 1997). The second development is theoretical and analytical analysis of the simple tools during the injection process. Both of the above developments have ultimately been directed towards achieving the goal of successful SL injection mould tooling. The results of such developments may help the industry to reduce the lead time and provide a faster technique in a concurrent engineering environment.

The first experimental results proved the capabilities of the technique and demonstrated its advantages and weaknesses. In addition, the important parameters in SL injection moulding such as injection pressure, injection speed, injection temperature, freeze time, cycle time etc. were investigated. The results and derivations may be used either as an instruction guide for industry users to design SL injection tools, or to provide design information for particular conditions and to predict tool failure.

2.0 Introduction

Initially, because of the diversity of parameters, it was not clear how the tool was going to behave or which parameters were important. Therefore it was decided to design a SL injection tool and use it in a real situation. After each experiment new questions arose, and after four consecutive experiments, a better understanding of the technique was built up. Therefore, based on this experimental understanding and successful results, an analytical approach was essential to understand more fully the process. The tool design is based on a parametric feature approach, where different prismatic features are varied in the X, Y and Z-axis. The first moulding was a 2mm thickness part composed of eight hollow prismatic cubes of 10 x 10 x 10 mm, based on a circular plate where all cubes were located radially at a pitch radius of 28 mm (*Figure 1*). The core and cavity incorporats a 1.5° draft angle to account for the injection moulding process (Menges 1986).

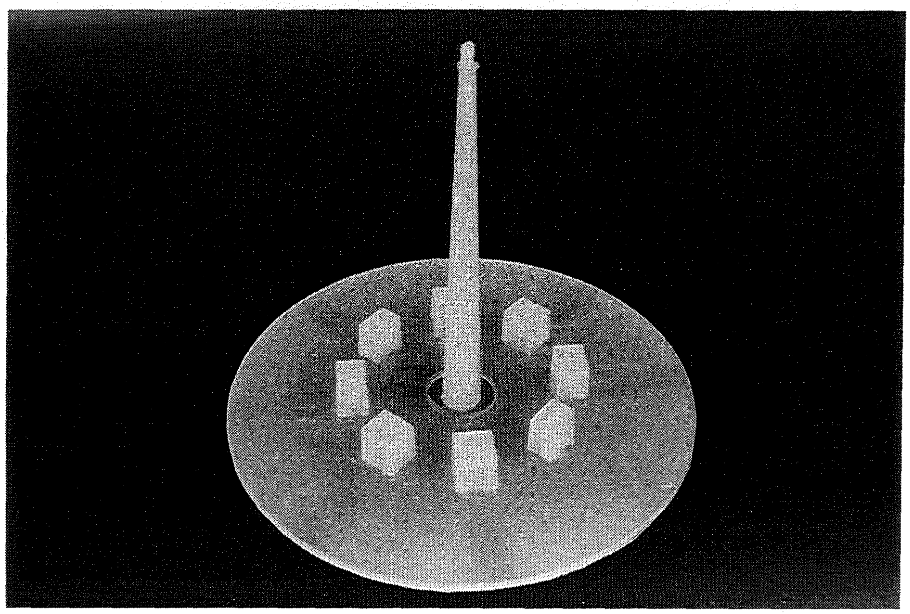

Figure 1. The moulding

A layer thickness 0.15-mm resulted in minimum stair stepping which was very helpful during moulding ejection. A sprue bush enters from the centre of cavity and fills the cubes uniformly. The large number of cubes may provide greater repeatability and better analysis of failure mechanisms. A total of 260 injections were made successfully without any tool failure. The plastic used was polypropylene (PP) which was injected at about 2000 psi. The next sets of tools were based on the same principle except the features changed in the radial width by increments of 1mm. Therefore the set would consist of two 10x10x10 cubes, two 10x9x10, two 10x8x10, and two 10x7x10 cubes. It was expected that this approach would indicate the limitations of the minimum web thickness or maximum web height.

SL moulds are placed in a steel sleeve and a steel plate behind the tool. The bolster assembly is set up (*Figure 2*) such that the actual tool is quickly interchangeable. This feature enables testing of different tools in minimum time. The SL mould is located into a 6mm thick steel sleeve and backed up by resin and aluminium chips to make it conductive and resistant to any compressive force during injection. Five pins of 8-mm diameter eject the part out of the mould. The ejector configuration will remain the same throughout the coming moulds, because all different prismatic shapes are placed on the same round plate (*Figure 1*).

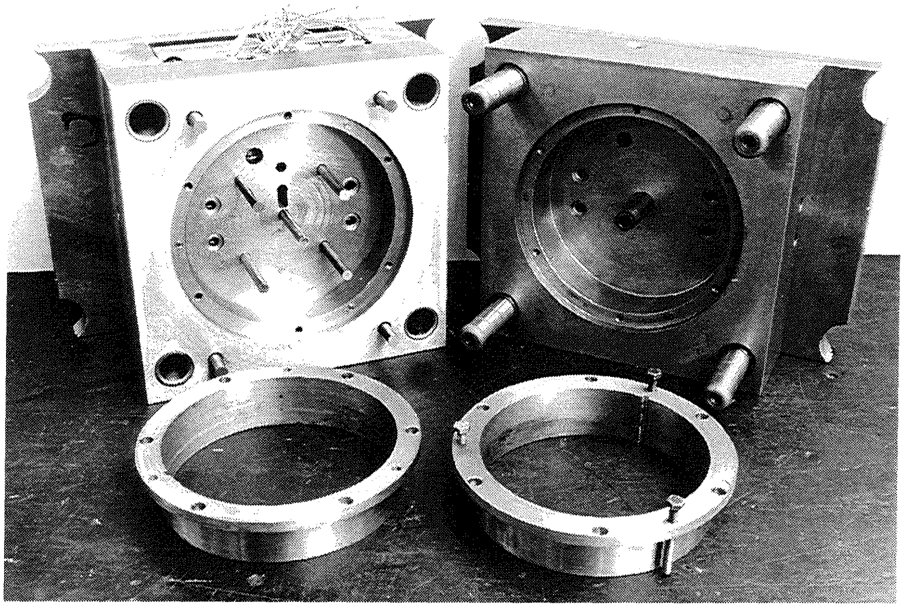

Figure 2. The complete bolster assembly

Following a large number of injections it was observed that when the flow hits one of the blocks it moves in three directions, upwards and around until the three flow fronts meet at the back symmetrically (*Figure 3*). The flow loses pressure as it moves away from the centre and in addition to this pressure loss the flow moving upwards faces additional loss due to the bends. There are two main forces acting on the block, one due to the shear stress acting on the base, the next is the bending stress trying to tip over the block. There is no clear indication of how the pressure profile is acting on the block as a function of time, so for the time being it is assumed that the resultant force is acting on the middle of block.

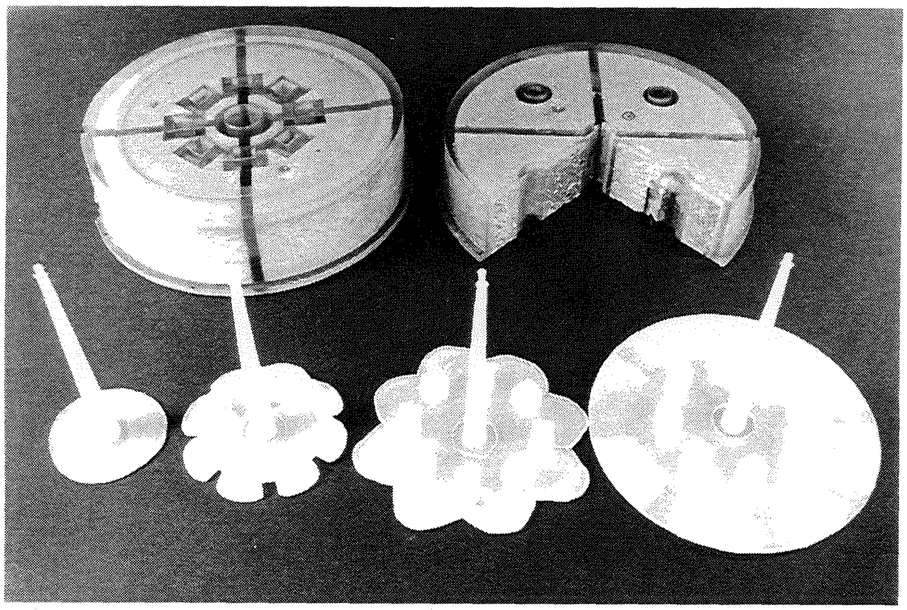

Figure 3. The flow progress sequence inside the cavity and a tool cross-section

3.0 Failure Mechanism Analysis

SL injection mould tooling has the potential of producing complex shapes at a rapid rate. SL tools have proved to be sufficiently strong when moulding PP plastics, for injections in excess of a few hundred parts (Rahmati 1997). Due to the lower thermal conductivity of SL tools, they must be treated slightly differently from metal moulds. The mould cannot be heated and cooled as quickly as with metals and hence a longer cycle time is inevitable. Using an air jet on the open tool has reduced a typical cycle time of 4-5 minutes to 1-2 minutes. However, the increased cycle time is not of prime concern in SL tooling in contrast to metal tooling where typically several thousands parts or more are required.

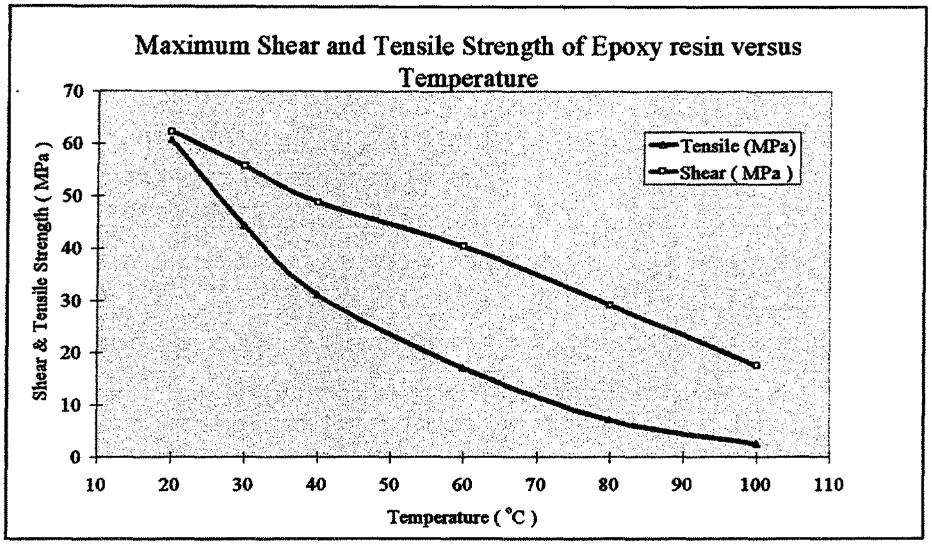

Figure 4. Maximum Tensile & Shear strength of epoxy SL5170 versus temperature

As tool temperature increases during injection, its strength continuously decreases (Ives 1971) until the maximum temperature is achieved (*figures 4 & 5*). This is the weakest situation of the tool, which may cause it to fail. The ejection time should be away from this weak point otherwise the core would be pulled off with the moulding during ejection. This is even more vital as materials with higher melting point and viscosity such as ABS, Nylon, or Polycarbonate are used.

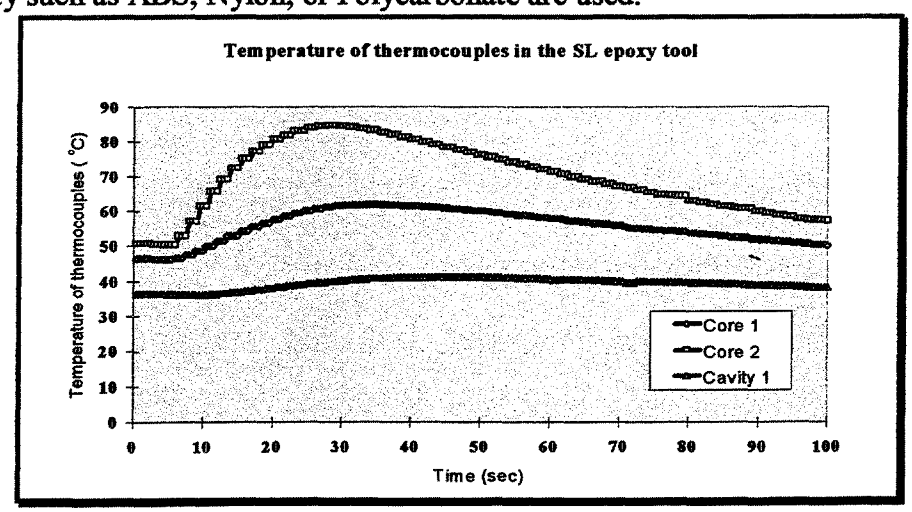

Figure 5. Temperature variation inside the epoxy tool during a cycle

It is important in SL tooling to remove the heat by all means. Three possible approaches are as follows which may be applied separately or as a combination of each. Cooling channels may add to the tool lead-time or cost. Therefore a more appropriate technique seems to be the first two by creating a conductive sink to absorb heat as much as possible and remove heat by air jet cooling.

- To backup the SL tool by conductive materials such as low melting alloy or aluminium chips or aluminium powder in conjunction with a resin. This will provide better conductivity as well as resistance against the injection pressure.

- To make the SL tool as thin as possible and apply the previous technique. This would provide even more conductivity and strength.

- To use cooling channels either in the traditional way or using conformal cooling channels. Regardless of increasing cost and overall lead-time, this may enable processing of thermoplastics such as Nylon or Polycarbonate.

SL tool failure falls into two main categories, first during initial injection, second during final part ejection from the SL tool. The first type of failure has occurred when the increase in temperature has weakened the material and the injection pressure is beyond the tool strength. Therefore when the molten plastic pushes through the cavity, if the instantaneous strength of the tool's particular feature is less than the injection pressure, it may cause that feature to break.

Secondary type of failures may happen during the final part ejection from the tool. When the part is ejected, the cube may be taken off the core and remain in the moulding. This type of failure is function of the following parameters:

- Stair stepping of the SL tool
- Draft angle on the tool
- Decrease in tool strength at increased temperatures

Stair stepping which is an inherent property of the SL process introduces more contact between the tool and moulding. This type of failure can be avoided by either delaying the ejection period or shortening it. However too early ejection cause the part to warp.

4.0 Pressure in SL Tooling

Pressure is acting instantaneously on the cube during injection. The pressure profile is derived from the strain gauges test mounted on the two ejectors (*figure 6*). As a matter of fact the peak pressure is higher than the average pressure (the integral of pressure over injection time), but the maximum pressure is acting on a limited area of the cube and only for a fraction of a second. Moreover the position of the peak pressure is continuously moving forward and therefore it is a fair assumption to apply the average pressure for the purpose of analytical calculations.

In general, at any instant where the injection pressure is higher than the tool strength, failure is feasible. To avoid this, care is taken to inject at a temperature where the tool material still has sufficient strength. This criteria has lead to a well defined cycle, where the new injection always takes place when the tool temperature has dropped to 45°C, where the material's strength is just enough to resist the injection pressure. Following this sequence regularly may help one to achieve a semi-automatic and consistent injection results.

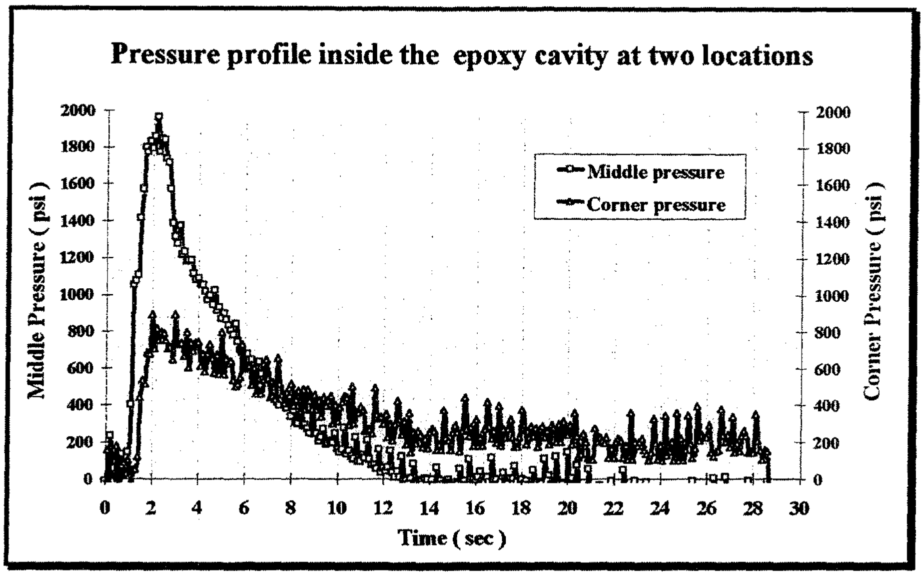

Figure 6. The pressure profile inside the cavity at the centre and after the cube

However, most of the failures observed were the result of not following this important guideline. Referring to *figure 4*, it is noticed that the tool's tensile strength has decreased to 25 MPa at 45°C which is enough for the tool to resist the injection pressure. Shear strength of the epoxy is investigated at different temperatures using British Standard 2782, method 341A, which is an approximation. This will determine the maximum possible temperature to begin the new injection in the cycle.

5.0 Flow Analysis

The molten plastic flow after impinging into the cavity, moves radially away from the centre where sprue bush is located. As the flow moves away from the centre it loses pressure, and in particular there is a sudden pressure drop as the flow gets to the blocks and moves upwards. Due to the fact the flow has high viscosity, low velocity, low density, and high pressure, the Reynolds number is not going to be very high which means that the flow within the cavity is *laminar*. Based on this fact it can be assumed that the flow within the cavity will create no *circulation* around the corners. This makes the flow analysis simpler.

6.0 SL Tool design Criteria

In general, to produce fracture, the ultimate shear and bending strength of the material must be exceeded. The assumption is that only *Shear and bending are the cause of failure* during injection. The base of the cube is the area which is resisting the melt flow during injection. Based on this assumption the important parameters affecting the tool failure would be the injection pressure, the moulding thickness, the cube height and the cube base area (shear area). Therefore the bending force and the shear force exerted to the cube as the result of the injection pressure are numerically calculated in the following section.

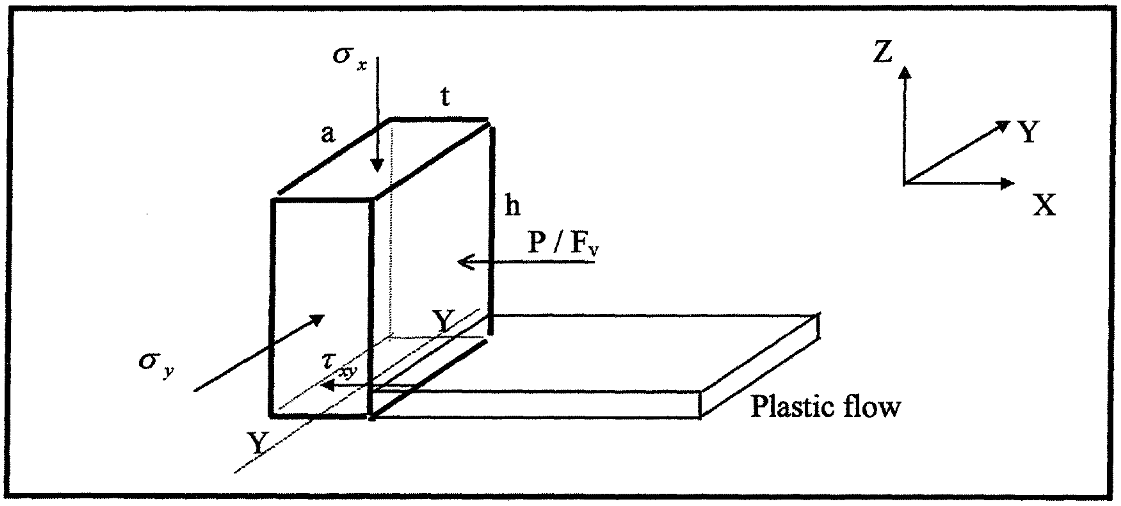

Figure 7. Schematic view of the flow and the block with parameters

Analytical Formulation of SL Tool Design

For design purposes, the largest stresses (both normal and shear stresses) are usually needed.

Ultimate shear strength of the Tool	$> \tau_{design}$	(1)
Ultimate bending strength of the Tool	$> \sigma_b$	(2)

where τ_{design} is the maximum shear stress applied to the tool during operation

σ_b is the maximum bending stress applied to the tool during operation

Since homogeneous, isotropic materials, when unrestrained expand uniformly in all directions when heated (and contract uniformly when cooled), neither the shape nor the shearing stresses and shearing strains are affected by temperature changes (Riley 1995).

$\mathbf{A_v = a * t}$	Cross-sectional area	(3)
$\mathbf{F_V = P * (a * h)}$	Shear Force	(4)
$\mathbf{M = \frac{(P * a)h^2}{2}}$	Bending Moment at root	(5)

$$\mathbf{I} = \frac{\mathbf{a} * \mathbf{t}^3}{12} \qquad \text{Second Moment of area of cross-section (about axis Y-Y)} \quad (6)$$

Where $\mathbf{F_v}$ is the shear force acting against the cube base
$\mathbf{A_v}$ is the effective sheared area (cube base)

Shear stress

$$\tau_{\mathbf{ave}} = \frac{\mathbf{Fv}}{\mathbf{Av}} \qquad (7)$$

$$\tau_{\mathbf{max}} = \frac{\mathbf{F_v}}{\mu \mathbf{A}} \quad \text{where } \mu = \frac{2}{3} \text{ (Gere 1990)} \quad \text{for rectangle, } \therefore \tau_{\mathbf{max}} = \frac{\mathbf{3}}{\mathbf{2}}\frac{\mathbf{F_v}}{\mathbf{A_v}} \qquad (8)$$

Bending stress

$$\sigma_{\mathbf{b}} = \frac{\mathbf{Mt/2}}{\mathbf{I}} \qquad (9)$$

Maximum in-plain shearing stresses

Having known the maximum stresses (equations 7&9) acting on an element in plane stress, we next consider the determination of the maximum in-plain shear stresses (Gere 1990).

$$\tau_{\mathbf{p}} = \sqrt{\left(\frac{\sigma_{\mathbf{x}} - \sigma_{\mathbf{y}}}{\mathbf{2}}\right)^2 + \tau_{\mathbf{xy}}^{\ 2}} \qquad (10)$$

where $\sigma_x = \sigma_b$
$\sigma_y = 0$ (because the side pressures on the blocks are symmetrical)
$\tau_{xy} = \tau_{ave}$

$$\boxed{\tau_{design} = \textbf{Maximum of } \tau_p \textbf{ OR } \tau_{\max}} \qquad (11)$$

7.0 Analytical Calculations of SL Tool Design

Maximum pressure at the point of injection:
σ **= 2000 psi = 13.79 MPa**
Average pressure in front of the cubes:
σ **= 663.5 psi = 4.575 MPa**
$\mathbf{A_v = a * t = 6 * 3 = 18\ mm^2}$

$$\mathbf{Fv = P * (a * h) = 4.575 * 10^6 \frac{\mathit{N}}{\mathit{m}^2} x (6 * 8 * 10^{-6}\ m^2) = 219.6\ N}$$

$$\mathbf{M} = \frac{\mathbf{(P * a)h^2}}{\mathbf{2}} = \frac{\mathbf{(4.575 * 10^6 * 6 * 10^{-3}) * (8 * 10^{-3})^2}}{\mathbf{2}} = \mathbf{0.88\ N.m}$$

$$I = \frac{a * t^3}{12} = \frac{6 * 10^{-3} * (3 * 10^{-3})^3}{12} = 13.5 * 10^{-12}\ m^4$$

Shear stress

$$\tau_{ave} = \frac{Fv}{Av} = \frac{219.6}{18 * 10^{-6}} = 12.2 * 10^6\ N/m^2 = 12.2\ MPa$$

$$\tau_{max} = \frac{F_v}{\mu A} \quad \text{where } \mu = \frac{2}{3} \text{ (Gere 1990) for rectangle,} \therefore \tau_{max} = \frac{3}{2}\frac{F_v}{A_v} = 18.3\ MPa$$

Bending stress

$$\sigma_b = \frac{Mt/2}{I} = \frac{0.88 * 1.5 * 10^{-3}}{13.5 * 10^{-12}} = 97.8 * 10^6\ N/m^2 = 97.8\ MPa$$

Maximum in-plain shearing stresses

$$\tau_p = \sqrt{(\frac{\sigma_x - \sigma_y}{2})^2 + \tau_{xy}^2} = \sqrt{(\frac{97.8 - 0}{2})^2 + 12.2^2} = 50.4\ MPa$$

$$\tau_{design} = 50.4\ MPa$$

According to the above calculations, τ_{design} is equal to the τ_p (i.e., τ_{design} = 50.4 MPa). This value must be compared to the Maximum in-plain shearing stress of the tool which is calculated as follows:

$$\tau_{tool} = \pm\sqrt{(\frac{31.05 - 0}{2})^2 + (48.81)^2} = 51.22\ MPa$$

where Max Tensile Strength at 40°C = 31.05 MPa
Max Shear Strength at 40°C = 48.81 MPa

Comparing τ_{tool} with τ_{design} one can conclude that tool must be able to resist the Maximum in-plain shear stress. The results shows a significant contribution of bending stress on the tool failure which means the height of the features play an important role in tool design.

8.0 Conclusions

Using a thermoplastic with a melting temperature of 200-300°C in epoxy SL tooling which has a Glass transition temperature of about 60-90°C, seems unrealistic or impossible. The key point to the success of this technique is the very low thermal conductivity of the SL tool and the short injection time (*figure 8*). These two factors are the key to the success of the SL injection mould tooling, which are overlooked by many.

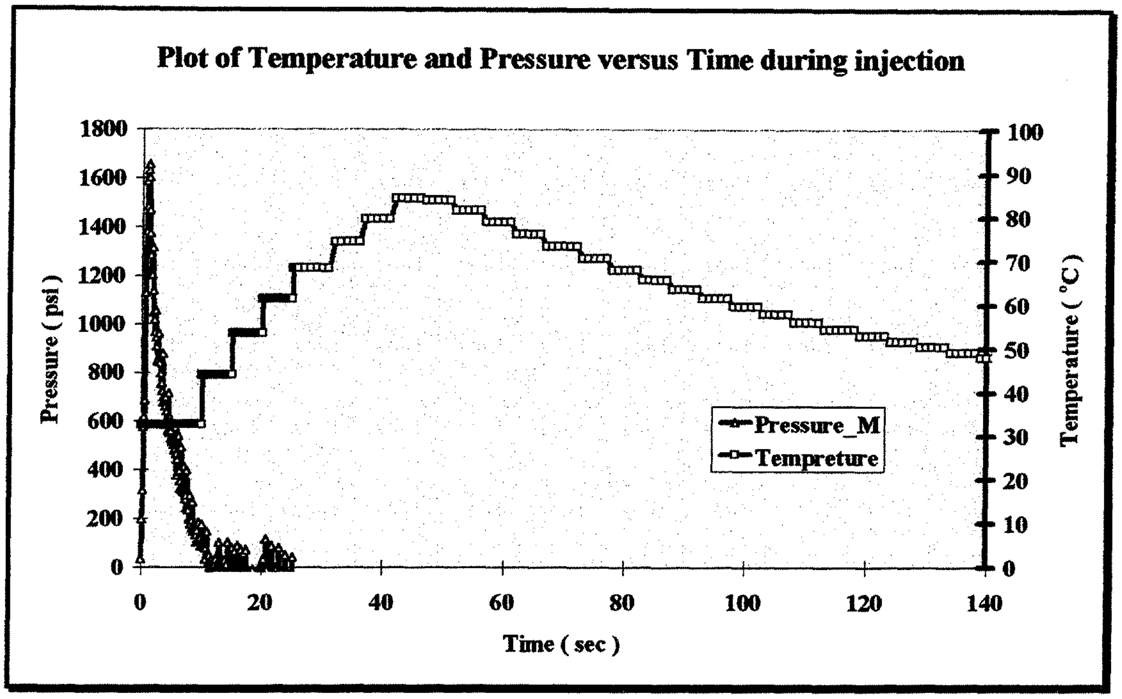

Figure 8. Plot of temperature and pressure versus time during injection

Although the epoxy has a very low tensile or shear strength at high temperatures, during the first few seconds, the maximum injection pressure is exerted on the tool, the heat has not been able to penetrate much (*figure 8*). Therefore the low conductivity of the epoxy works in favour of the process initially. It can be concluded that the tool must be cooled down to as low as 30-40°C before the next injection is made. This may increase the cycle time, but the tool success has the priority. At this point the tool temperature after new injection would not increase much and the tool failure could be avoided. This cooling can be achieved either through free convection which takes 4-5 minutes or through forced cooling by means of air jet which reduces the cycle time to 1-2 minutes.

9.0 References

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