Application and Modelling of Hybrid Stereolithography Injection Mould Tooling

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Keywords

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Abstract

The use of stereolithography (SL) to make injection moulding tools has been shown previously to be an efficient way of producing rapid tools for simple geometries, aiming at small lot sizes with an acceptable degree of accuracy. This paper highlights the unexplored potential of using SL inserts in hybrid tools using practical experiments and FEA mould filling models. The practical experiments reveal problems incurred by uneven flow as a result of differential thermal conductivity between dissimilar mould materials in a hybrid tool. The FEA flow models confirm that this uneven flow would be anticipated when using FEA software. A further FEA stress analysis predicts that catastrophic mould failure will be expected under some conditions and these reflect the results found in the practical experiments. The use of a homogeneous SL tool eliminates the issues caused by uneven mould filling but results in thermal distortion of the female mould. Ultimately a SL tool backfilled with low melt point alloy provides a solution that eliminates the problems of uneven filling and thermal distortion.

1 Introduction

1.1 Rapid Tooling

Over the past years rapid tooling (RT) has been largely seen as a complementary technology, for quickly making tools for various kinds of prototype applications, within the tooling sector (Wohlers, 2004). In some cases, depending on part requirements and lot sizes, rapid tooling techniques have successfully substituted conventional tooling methods (Hilton and Jacobs, 2000). With a focus on saving significant amounts of time and money, SL tooling is one technique that can be adopted for making tools for injection moulding with low-medium complexity, albeit with small-medium outputs (Hopkinson and Dickens 2000a).

1.2 Stereolithography-based Injection Mould Tooling

Research into the use of SL inserts as injection moulding inserts began in the mid 1990's when the process was first developed and marketed by 3D Systems as the "Direct AIM™" process (Decelles and Barritt, 1996). Injection moulding parameters were first investigated by 3D Systems and it suggested the use of extended cooling throughout the mould cycle (Jacobs 1996). Further analysis of mould cooling suggested that the use of extended in-mould cooling prior to ejection should be avoided as this maximises the risk of catastrophic failure during part ejection (Hopkinson and Dickens, 2000b). Further work considered the optimisation of tool design to minimise the risk of tool failure during injection and during part ejection (Palmer and Colton, 1999, McDonald et al 2001).

SL resin development for injection moulding saw much interest in the 1990's especially with regard to the production of resins with higher glass transition temperatures (Tg) than the commercially available materials. Most SL resins have a Tg around 60-70 °C, however research lead to higher Tg's of 112-145 °C (Schultz et al, 1997, Ullett et al, 1997). It was found however that the SL resins with higher Tg tended to be more brittle than conventional SL resins which made them susceptible to failure under load during moulding filling when used for injection moulding (Harris, 2002).

The other major area of research for injection moulding using SL tools focussed on the material properties of parts produced. A wide variety of thermoplastics including polypropylene (PP), polystyrene (PS), polyamide (PA/nylon), polycarbonate (PC), polyether-ether ketone (PEEK) and acrylonitrile-butadiene-styrene (ABS), have successfully been injection moulded using SL tools (Hopkinson and Dickens, 1999, Luck et al, 1995, Eschl, 1997, Harris, 2002 and Sculthess et al, 1996). The cooling rate within a SL tool has been shown to affect the mechanical properties of moulded parts when compared with those produced in steel tools. In general the slower cooling rate found in SL tools results in a higher degree of crystallinity in semi-crystalline moulded parts leading to increased tensile properties but reduced impact properties (Dawson, 1998). Increased crystallinity was also shown to affect shrinkage rates in nylon (semi-crystalline) parts that had been moulded in SL tools (Harris, 2002). Amorphous materials tended not to be affected by cooling rates and thus exhibited similar properties when moulded in both SL and steel moulds (Dawson, 1998).

1.3 Hybrid Tooling

Hybrid tooling describes a process where various rapid and conventional tooling technologies and/or materials are used in a single tool in order to optimise the overall characteristics and cater to the requirements of the tool. Though not explicitly referred to as hybrid tooling, such techniques have been around since rapid tooling has emerged, based on the expertise of individual model makers and tool makers.

1.4 Objectives of this study

The purpose of this paper is to present research performed jointly by DaimlerChrysler AG, Loughborough University and Duisburg-Essen University into the performance of hybrid injection moulding tools incorporating SL inserts along with steel inserts. The study involved a practical analysis of tool performance along with FEA analyses to explain mould filling behaviour and its effects on tool functionality.

2 Practical Moulding Methodology

2.1 Test part design

Figure 1 shows the test part for which the experimental and computational studies were performed. The dimensions of this test part are 150 mm x 50 mm x 50 mm, with a taper of 0.8°. The wall thickness is 2 mm throughout. Other features include two diagonal ribs as shown and a uniform fillet of 0.8 mm radius at the intersections. This geometry was chosen because it enabled the testing of the following effects:

1. Effect of the various mould inserts on filling, especially along the ribs. From figures 1 and 2, it can be seen that the ribs are enclosed by a homogeneous material, that of the core insert. It was desired to study the influence of the SL core insert on heat transfer along the ribs
2. Effect of process pressures on the upstands of the core (male) inserts

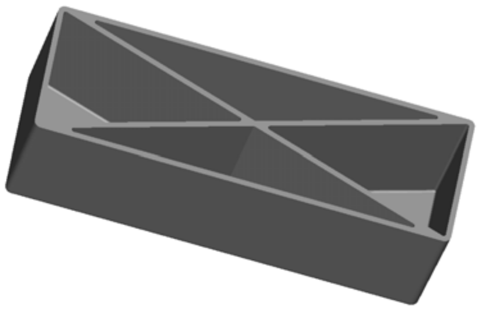

Figure 1
Test part

2.2 Mould design

Figure 2 shows a basic set-up of the mould used during the experimentation, with a SL insert representing the core side of the mould. The SL inserts were positioned in a pocket, as illustrated in figure 2; the tool operated in a simple open-close movement and no additional sliders were used. This was done in order to keep the number of possible variables to a minimum and to enable the operator to change the inserts quickly. Apart from the mould configuration depicted here, a mould containing SL inserts on both the core and cavity sides was also subjected to experimentation, to compare and contrast the homogeneous and hybrid mould set-ups.

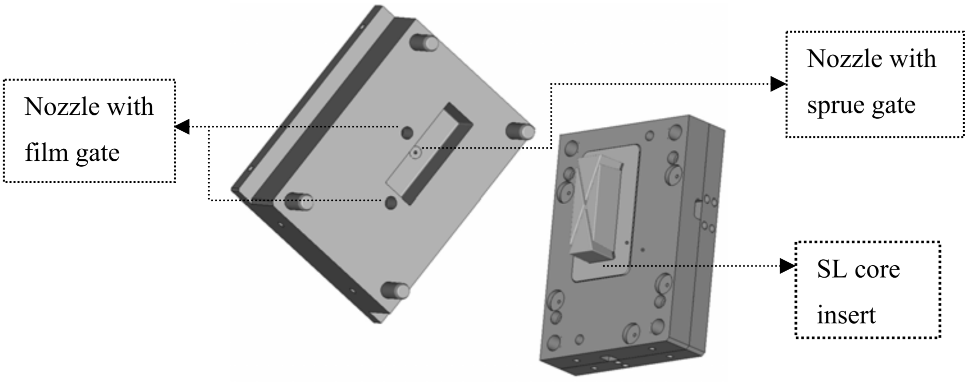

Figure 2
Hybrid tool showing the stereolithography insert

Three different gate positions were used during the moulding trials, out of which two were designed to inject from the sides and one from the top surface, with respect to the part geometry. The former were of film injection type and the latter, sprue type. It was preconceived rightly that the sprue type posed the greatest threat to the stability of the insert, mainly due to the excessive mechanical stresses. After the initial trials with a mould combination of SL insert core and tool steel cavity in which all the three gate positions were used separately, only one gate position that induced failure possibility the least, was deployed for subsequent trials with other moulds. This gate was located on the shorter side (breadth) of the cavity, refer figure 2.

A standard cooling system, represented by straight copper tubes of 10mm diameter, was employed on the cavity of the mould, as shown in figure 3.

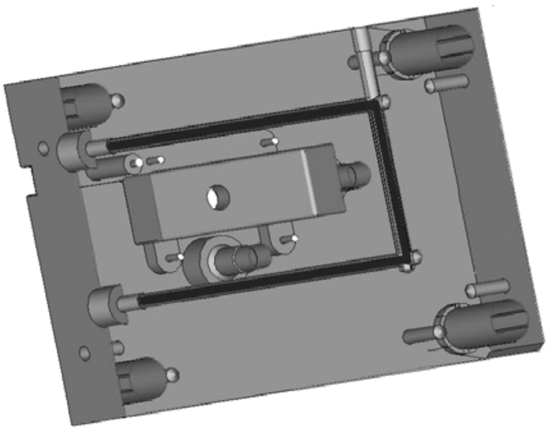

Figure 3
Cavity side cooling

Two K-type thermocouples, one each on the cavity and core sides of the mould, were used in order to record the temperature history within the mould. In the cavity side, a thermocouple was placed through a drilled hole, as shown in figure 4. The core side temperature was measured at the end of each cycle, by manually placing a thermocouple, in such a way that the temperature values were measured at a location that corresponded to that in the cavity side.

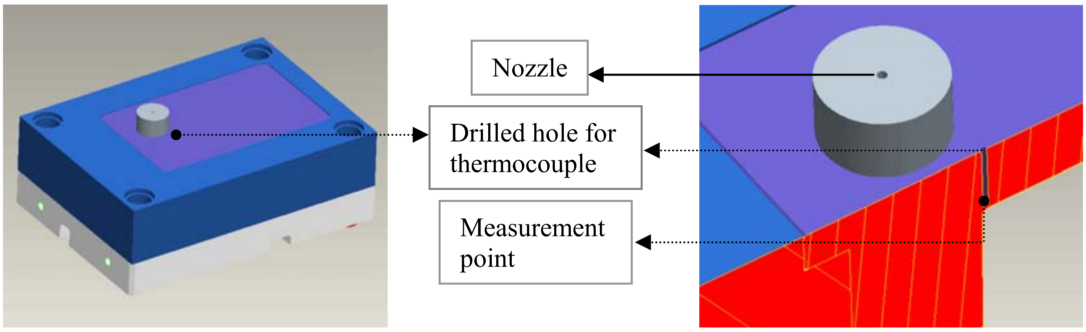

Figure 4
Location of thermocouple on the cavity side

2.3 Moulds tested

Table 1 presents a list of the mould configurations that were tested:

Mould Nr.	Type of mould	Core side	Cavity side
1	Hybrid	SL insert	tool steel
2	Homogeneous	SL insert	SL insert
3	Hybrid	SL insert with epoxy resin backfilling	tool steel
4	Hybrid	SL insert with LMA backfilling	tool steel

Table 1 – Types of moulds tested

The first and the most basic hybrid system consisted of a SL insert representing the core side of the mould, and tool steel representing the cavity. Initially, only homogeneous SL core inserts were used in order to restrict the number of variables during experimentation and to determine whether complex features within the SL mould could be realised directly without the need for reinforcement of critical areas. Figure 5 illustrates the kind of inserts that were used during experimentation. Two different resins, SI40 and SL7580, were used for the SL insert generation.

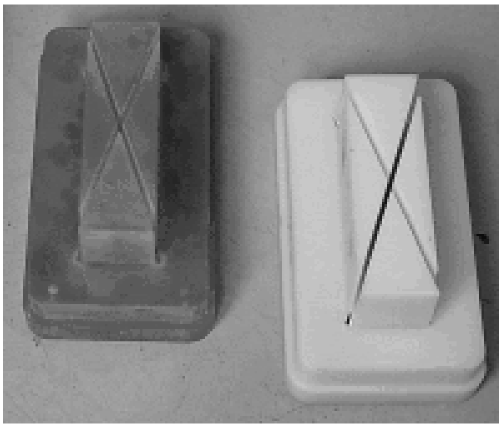

Figure 5
SL inserts

Based on the know-how from testing the above-mentioned mould set-up, it was decided to make the SL inserts heterogeneous by backfilling, in order to improve their thermal and mechanical characteristics. Two different backfilling methods were deployed, one using a low melting-point alloy (LMA) and the other, using an epoxy resin. The thought process behind the deployment of LMA for backfilling was to improve the stability of the insert as well as to improve the heat transfer characteristics. It was decided to use epoxy resin as a backfilling material, only to improve the stability of the insert i.e., to arrest or minimise the deformation of the insert, due to thermal and mechanical stresses. The response of the homogeneous SL mould was also recorded simultaneously.

2.4 Manufacture of moulds

All SL parts (complete inserts and shells to be backfilled) were manufactured in a 3D Systems SLA7000 machine. Solid SL inserts were made from both SI40 resin and from SL7580 resin. SI40 inserts had proved too brittle for moulding and so backfilled SL shells were only made from SL7580 resin and their manufacture is described below.

The SL shells that were used for this investigation were of two sizes: a 3-mm shell and a 5-mm shell. It was anticipated that the former would aid in better heat transfer than the latter and the latter would be more stable, mechanically.

Epoxy backfilled shells were backfilled in one step i.e., the shell was completely filled with the resin in one pouring procedure. However, backfilling with LMA, which is an alloy of bismuth (58%) and tin (42%) marketed under the name *Cerrotru*, had to be done in a layer-by-layer procedure, due to it's higher melting point (138°C) and after pouring each layer, the heat had to be removed from the shell by forced convection, resulting from the usage of an air-pistol. This was done with utmost care, ensuring that the insert, at no point of time, was subjected to distortion. Also, the pouring process was done in such a way that an even spread of the LMA on the surface of the insert was ensured, so that differential heating/cooling was avoided. Probably the most important aspect of backfilling the insert, especially in the geometry under study, was to ensure that the backfilling material reaches all the sharp corners, as they were dimensionally awkward but critical nevertheless. The SL shell and the backfilling process are shown in figure 6. Concerning the mould insert manufacturing times, the shell-type SL mould inserts were produced and finished in two days. While the epoxy backfilling was done externally, the LMA backfilling was done in-house. The entire process of step-by-step filling and drying of LMA, followed by finishing, took about two hours.

Figure 6
SL shell (left) and backfilling process

2.5 Injection moulding parameters

The injection moulding machine that was used to mould the parts, was a Krauss Maffei KM 80/390/C1 machine, 80 standing for 80 tonnes of clamping force. The same machine was used throughout the experimental procedure, to ensure the consistency of the investigation. The material that was used for the component part was a PP, HE125MO, made by Borealis. It is a non-reinforced, non-filled homopolymer, specifically designed for injection moulding applications. PP was chosen because of the fact that the test geometry was aimed at verifying the capability of the tooling methods under study and to qualify them for deployment in producing a set of components that are used in real life situations. These parts are, in general, made from PP. Also, the properties of PP are such that it was conducive to moulding trials with the mould configurations under study; glass-filled plastic materials tend to abrade the insert and some materials like PA are hygroscopic in nature, resulting in the exclusion of such materials from consideration. Also, the resins deployed for the experimentations are stable only up to a melt temperature of 250°C.

The process parameters that were used for the injection moulding runs are:

Parameter	Value
Filling time [s]	2.81
Packing time [s]	-
Melt temperature [°C]	235
Mould temperature [°C]	50
Coolant inlet temperature [°C]	50
Coolant flow rate [l/min]	6

Table 2
Injection moulding parameters

The information from the sensors was accumulated using a multimeter; the temperatures in the mould were measured in a systematic manner, at the same time intervals. This was done to ensure the uniformity of the measured data.

3 Practical moulding results

3.1 Mould 1 (core: SL insert; cavity: tool steel)

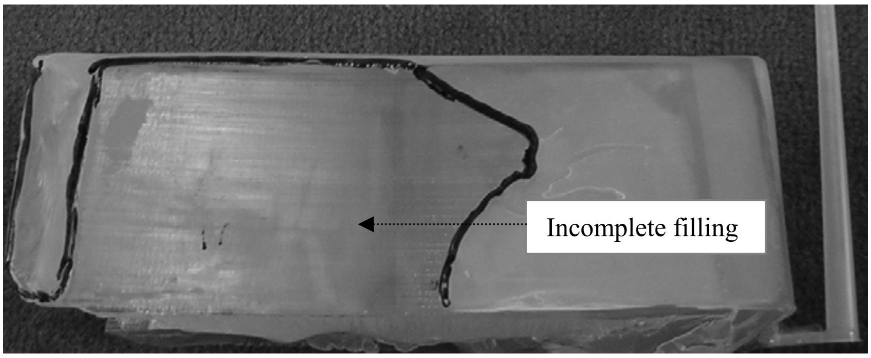

Figure 7
Fill behaviour with steel/LMA hybrid tool (top) and steel/SL hybrid tool

Figure 7 shows the partial moulding created from Mould 1. It can clearly be seen that mould filling was uneven, resulting from the relatively free melt flow through the centre of the mould (i.e. along the ribs) than at the edge of the mould. Given that the wall thickness was constant at 2 mm this uneven flow may be attributed to the difference in the thermal conductivity of the two mould materials. The core side has a low conductivity and so the polymer melt remains fluid with a low viscosity as it passes through the rib areas, whereas the cavity has a much higher conductivity, causing the melt to cool, thereby increasing its viscosity and freezing it before mould filling is complete. This resulted in a differential pressure distribution and since the insert had upstands with higher-than-recommended aspect ratios, they lost their stability due to the combined effect of pressure and temperature and the mould failed without yielding a single completely filled part. This uneven mould filling resulted in higher pressure in the rib area, causing a force to push the mould upstand outwards and thus reducing the wall thickness on the outside of the part. This compounded the difficulty of flow as the melt forming the outside wall cooled quicker still as its wall thickness reduced.

Figure 8 shows the temperatures measured by the core and cavity thermocouples at the end of consecutive cycles. It is not to be misinterpreted that each cycle yielded a complete part; on the contrary, due to the abovementioned reasons, not a single completely filled part was able to be obtained. Also, the temperature values that are found in the graphs that are presented here represent the temperatures starting from trials to estimate the exact values of parameters like melt volume, velocity etc., up to the cycle when the tool failed. The thermocouples were located such that they were very close to the gate, so that even during partial filling, they were always in close proximity to the melt and hence, the temperature values presented here are fairly reasonable. As would be expected, the core side heats up more (82°C) than the cavity (30°C) as the moulding shrinks on to the core and maintains a better thermal contact with the mould surface. The core material also has a lower thermal conductivity than the cavity and this further explains the temperature differences measured.

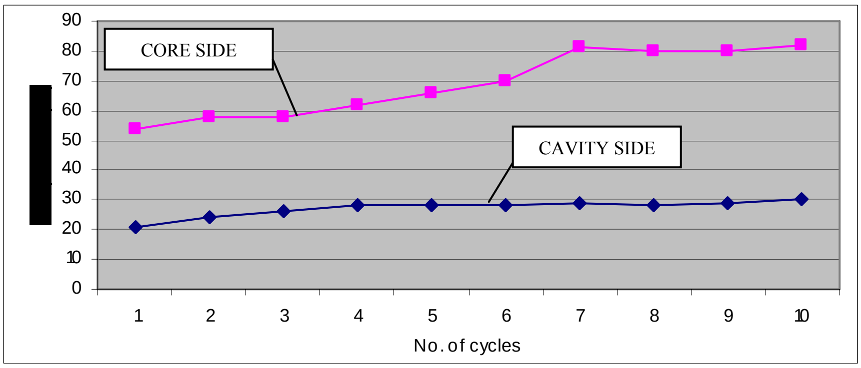

Figure 8

Temperature history of SL-tool steel mould

3.2 Mould 2 (homogeneous SL mould)

The homogeneous SL mould, which was deployed to identify whether a uniform filling of the mould could be obtained as a result of material homogeneity, gave rise to another kind of problem, namely the distortion of both the inserts due to thermal expansion along with the transgression of the glass transition temperature of the resin, resulting from high temperature values. There was a relative displacement of the two halves of the mould and effectively no parts were obtained from this tooling set-up.

Figure 9 shows the tool temperatures measured by the thermocouples in the core and the cavity. The temperature in the core increases in a manner similar to that of Mould 1 to a maximum of 83°C; however the temperature rise in the SL cavity is greater (62°C) than that measured in Mould 1, which had a steel cavity. These readings are consistent with the theory that thermal mass plays an important role in the temperatures encountered and that shrinkage of the part onto the core results in higher heat transfer than in the cavity side of the mould. These results are consistent with previous observations using SL tooling (Hopkinson, 1999).

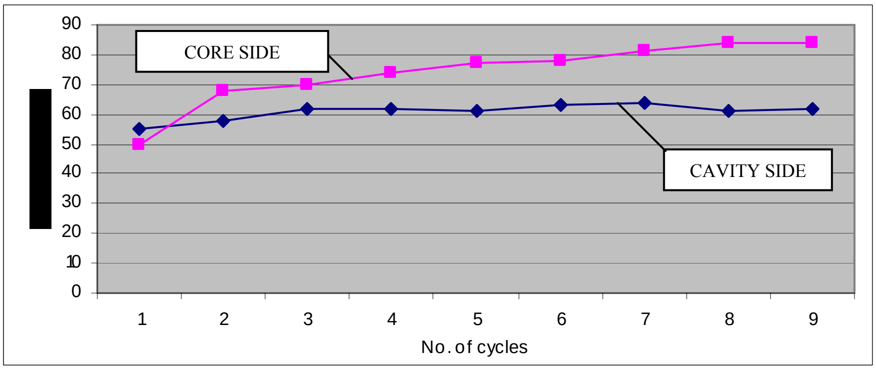

Figure 9

Temperature history of homogeneous SL mould

3.3 Mould 3 (core: SL insert with epoxy resin backfilling; cavity: tool steel)

As far as the insert that was back-filled with epoxy resin is concerned, the backfilling did not result in better mechanical characteristics as expected; this set-up also did not produce a completely filled part. The insert failed, which could probably be attributed to the wrong selection of the epoxy resin. Further experiments are underway in this regard, which involves the usage of a more suitable tooling resin. As figure 10 shows, the usage of epoxy resin with slightly better thermal conductivity resulted in a slight reduction in the maximum temperature values; the values of ΔT remained high nevertheless.

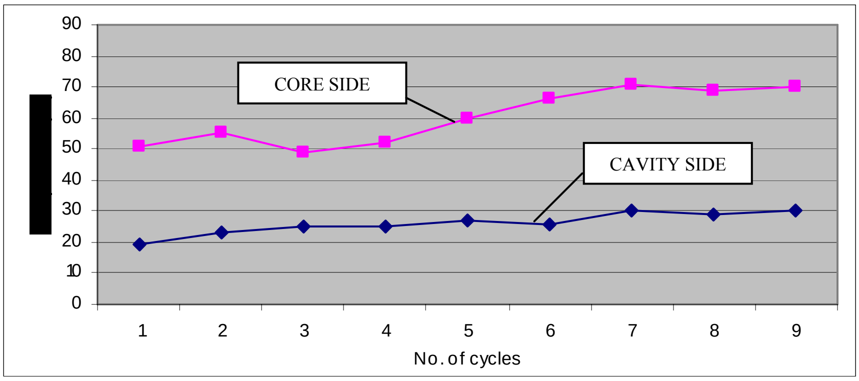

Figure 10

Temperature history of epoxy resin backfilled SL-tool steel mould

3.4 Mould 4 (core: SL insert with LMA backfilling; cavity: tool steel)

This tool gave the best performance in terms of quality of the parts produced. This exhibited a fill behaviour, which is comparable to the behaviour of a homogeneous steel tool, see figure 11.

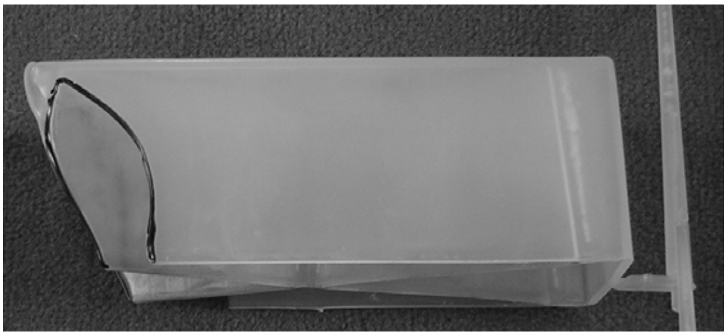

Figure 11

Evidence of even mould filling from the LMA backfilled core mould

Figure 12 shows the temperatures recorded by the thermocouples in the core and cavity sides of the mould. The temperature distribution in the insert was quite uniform i.e., ΔT values were low. This type of tooling exhibited uniform and effective heat removal, entirely attributed to the backfilling material. Also, this backfilling material has an inherent advantage: the material is recyclable.

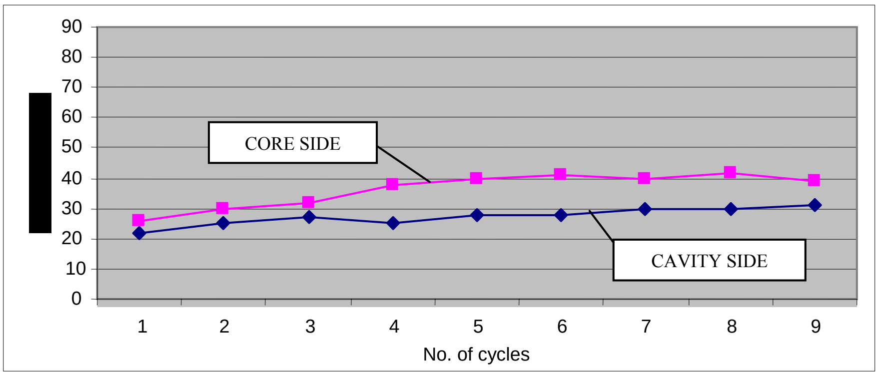

Figure 12

Temperature history of LMA backfilled SL-tool steel mould

This mould produced two completely filled parts. It failed after a few shots, due to the layered build-up while backfilling. This resulted in air-gap between the adjacent layers, as shown in figure 13, which undermined the insert. Also, air-gap was present in the contact area between the SL shell and the backfilling material, due to the shrinkage of the latter. Since there was no provision to compensate for this shrinkage, the insert was used as such, which also undermined it.

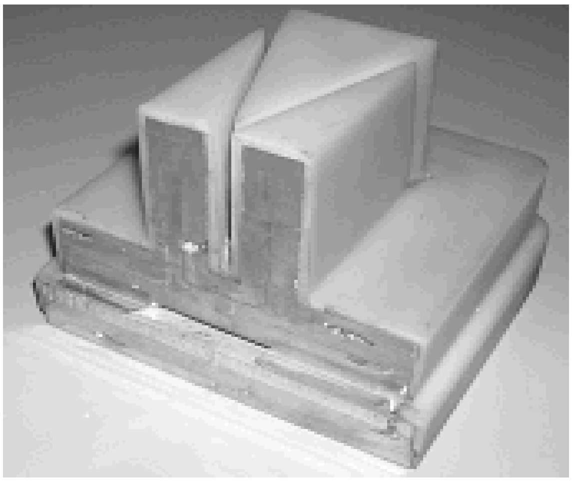

Figure 13

Layered backfilling with air-gaps

It could be inferred from figure 12 that the mould with tool steel on the cavity side and SL insert with LMA backfilling on the core side exhibited not only low temperatures that are comparable with a homogeneous tool steel mould, but also a very less temperature difference (ΔT) between the two halves, indicating the uniformity of temperature distribution. This behaviour is very much desirable, as the resulting part characteristics tend to be homogeneous, besides prolonging the life of the insert.

3.5 Discussion of practical moulding results

The results of the practical investigation were really informative in understanding and ascertaining the behaviour of the various tooling combinations under study. The hybrid set-up of the moulds was in fact, played a decisive role in producing a completely filled part. The results clearly illustrate where the homogeneous SL tooling, SL insert without backfilling and SL insert with epoxy resin backfilling fall short of demands and where the SL insert with a LMA backfilling scores over other methods.

4 FEA modelling methodology

Injection moulding is one of those processes in which the visualisation of what is going on during the process is difficult, as the interior of the mould is not always accessible to human eye/recording devices, during the process. That is why backing up the experimental results with numerical simulations is almost indispensable. In the current study, since the mould configuration was all the more complex due to the material heterogeneity, it was decided to make use of simulation software, to get an in-depth knowledge of the influence of the process parameters on the mould set-up and the possible failure modes.

A typical injection moulding process simulation was carried out using *Sigmasoft*, a 3D simulation software and a subsequent mechanical (stress) analysis was performed using the FEA software *Algor*. The mould with a SL core and tool steel cavity was chosen for the simulations, as it was the base model around which other mould configurations were developed.

4.1 Mould filling simulation parameters

In Sigmasoft, there is a provision to incorporate any number of sensor nodes, in order to gain an insight into the process history. In the current study, sensor nodes were set-up throughout the mould, in order to obtain valuable temperature and pressure data throughout the duration of the simulation. It was ensured that such sensors were placed in the same locations for different simulation runs, in order to compare and contrast these parameters that eventually decide the tool life.

The simulation parameters that were used for Sigmasoft simulations are:

Parameter	Value
Filling time [s]	2.8
Number of simulated cycles	20
Melt temperature [°C]	235
Mould temperature [°C]	50
Temperature of the tempering medium [°C]	50
Flow rate of the tempering medium [l/min]	6
Packing phase duration [s] and pressure [bar]	5, 350

Table 3

Sigmasoft simulation parameters

4.2 Stress analysis on male tool insert

A mechanical (stress) simulation was performed using *Algor*, so that the jigsaw puzzle was complete. Making use of the data obtained from Sigmasoft, the model for this FE analysis was configured. Since the prime objective of this simulation was to ascertain the response of the upstands to the loads caused by the pressure of the melt, a simplified model with only the male tool insert was simulated.

5 FEA results

The results of the simulations more or less validated the results of experimentation. They reiterated our assumptions regarding the failure of the inserts due to excess pressure on the upstands with high aspect ratios. These simulations went hand-in-hand with the experimental findings and were really useful in ascertaining the process / failure mechanisms.

5.1 Mould filling behaviour

Figure 14 represents the temperature distribution on the SL insert, the core side of the mould, at the end of the moulding cycle. The temperature values on one side of this insert are decidedly higher than those on the other side, indicating the incomplete filling of the mould cavity. Figures 15, 16 and 17, displaying the temperature, pressure and velocity distribution respectively on the component part, presents a clear picture of what really happened during the moulding cycle. These results demonstrate without an iota of ambiguity that the temperature, pressure and velocity values were much higher in the areas representing the ribs of the component part, in comparison with other areas.

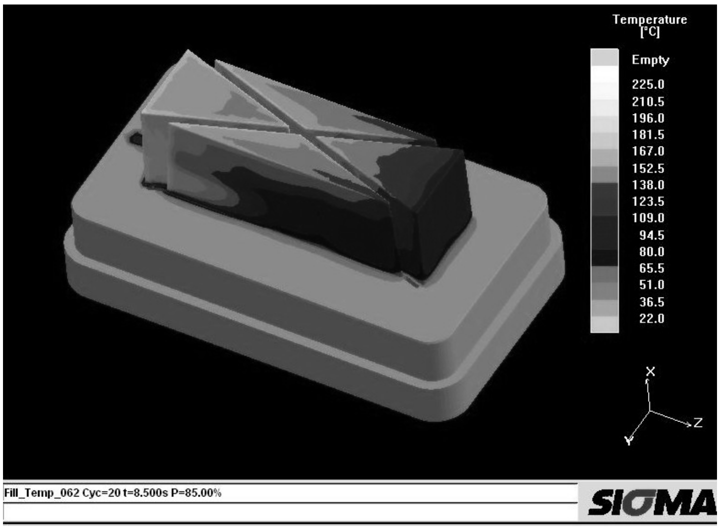

Figure 14

Temperature distribution on SL insert

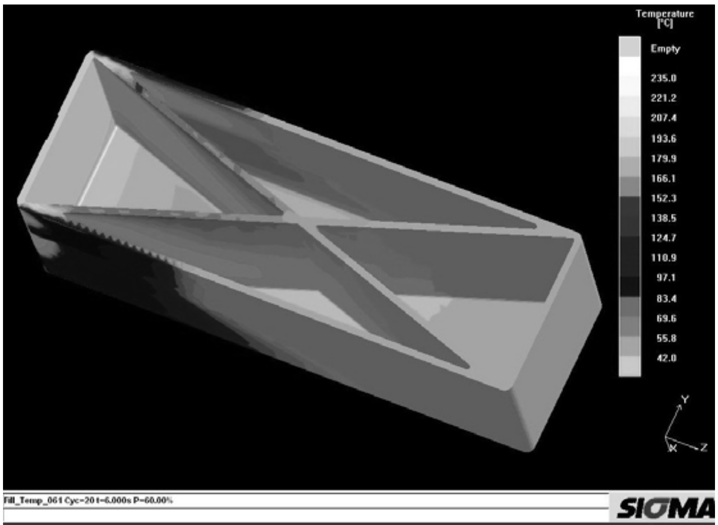

Figure 15

Temperature distribution on component part

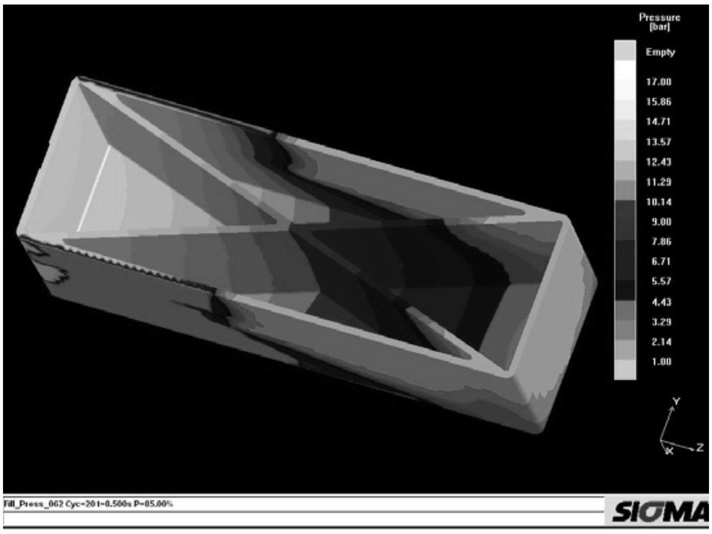

Figure 16

Pressure distribution on component part

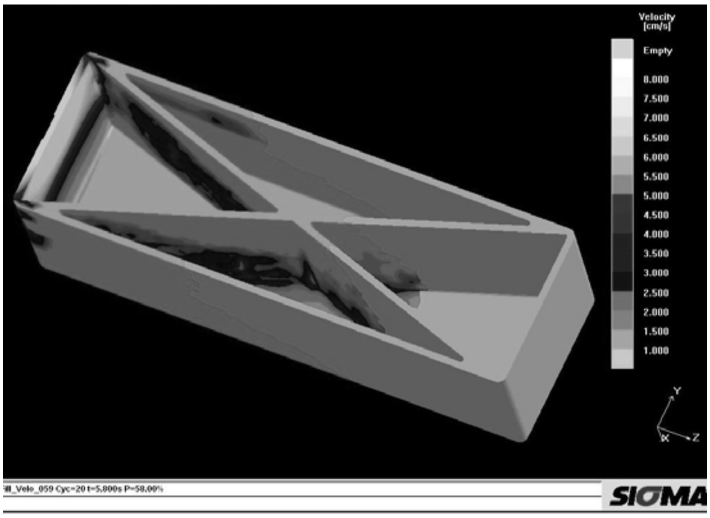

Figure 17

Velocity distribution on component part

5.2 Stress analysis on male tool insert

It could be inferred from the mechanical simulations that the maximum stress values were concentrated on the base of the upstands, as shown in figure 18 and the maximum displacement, at the top, as in figure 19. The plausible reasons for such behaviour are as follows:

- The aspect ratios of the upstands were quite high, thereby leading them to act as cantilever beams. Due to this, the deflection values at the top of the upstands were maximum
- The stress distributions were highest at the base of the upstands due to their cantilever action, due to which the gap i.e., the mould cavity was at its smallest near the base and maximum at the top. With the increasing gap at

the top, the stresses decreased and since there was virtually no change in the gap at the base, the stress values were higher there

Thus, the concatenation of the results from experimentations and simulations resulted in the determination of behavioural characteristics of various mould combinations, in an unambiguous manner.

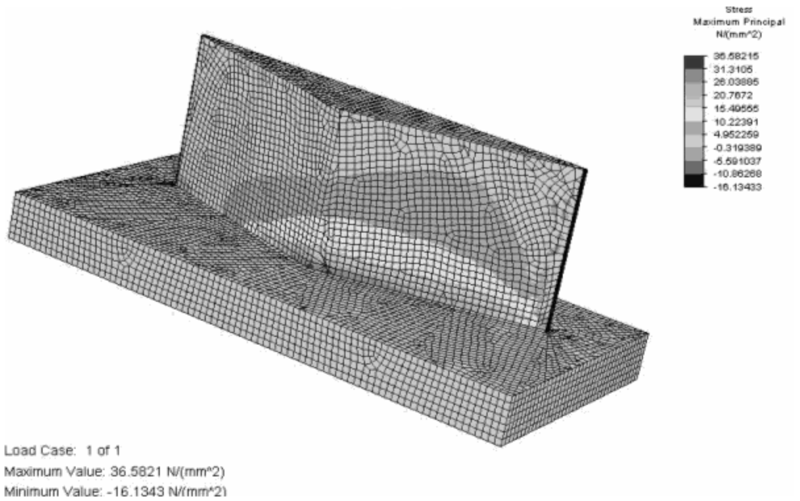

Figure 18

Stress distribution on a part of SL insert

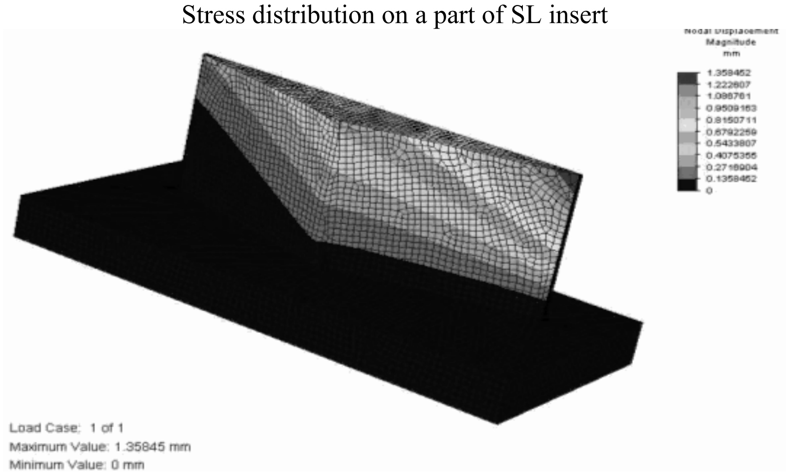

Figure 19

Displacements on a part of SL insert

6 Conclusions and recommendations

The practical results reveal the problems with uneven mould filling when inserts of different conductivity are used. This can result in fracture of the male upstands during moulding. The FEA mould filling simulations replicate the uneven mould filling observed in practice. The mould pressures were transferred into an FEA stress analysis model and used to predict failure of the male upstands under bending as observed in the practical trials. The backfilling of SL inserts with LMA has proved to be advantageous in the sense that it aids effective heat transfer besides stabilising the insert, demonstrated by the fact that homogeneously filled parts were obtained.

Also, since the stability of the SL insert that is backfilled with LMA still leaves a lot to be desired due to the layered filling of the latter, an improved approach, in which the SL shell is backed-up by a network of ribs, has been proposed. The thought process behind this is that this rib network, designed to minimise distortions due to thermal influences, will enable the backfilling of the SL insert in one pouring step, thereby eliminating the problems posed by layered filling. Figure 20 shows the ribbed SL insert which is to be subjected to further moulding trials.

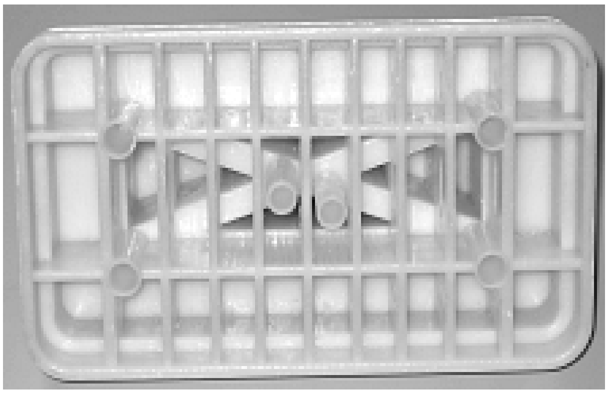

Figure 20

SL insert with rib network

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