

Hybrid moulds: the use of combined techniques for the rapid manufacturing of injection moulds

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ABSTRACT: Injection moulding is the major polymer processing technique. The mould is a key element of this process and its characteristics have a key importance on the parts produced. The fabrication of products with higher added value, especially in terms of production time and costs, is essential for the success of the mouldmaking industry within a global competitive environment.

This paper presents the concept of hybrid mould, a recent concept for injection moulding of prototype and short series. Direct and indirect rapid tooling technologies can be used for the fabrication of these moulds. Hence, new design guidelines need to be defined to produce these moulds as well to assess its performance.

Epoxy tooling and selective laser sintering are the two rapid tooling technologies explored to produce inserts for hybrid-moulds. This work studies the fabrication of hybrid-moulds through these rapid tooling technologies, as well its mechanical and thermal behaviour.

1 INTRODUCTION

In today's highly competitive marketplace with short life-cycles of products, to develop a new product to meet consumers' needs in a shorter lead-time is crucial for an enterprise. Facing this global environment, the strategy of developing a product is transformed from "product-push" type to "market-pull". To improve competitiveness, a product should not only satisfy consumers' physical requirements but also their needs, increasing the product complexity and reducing its lifetime. Apart from this, market segmentation as a demand of individualistic consumers has led to the concept of "niche markets", increasing product choice. Additionally, companies must meet increasing customer expectations in terms of products' quality and cost. These new strategies adopted by modern companies lead to a tremendous change in their internal flexibility. As a consequence, the current industrial trend is moving from mass production, *i.e.* high-volume and small-range of manufacturing products, to a small-volume and a wide range of products. This has resulted into a remarkable industrial transformation, described by Rosochowski and Matuszak (2000) as the world class manufacturing concept, characterised by: (1) total quality, (2) concurrent/simultaneous engineering, (3) short manufacturing lead-times, (4) high flexibility to enable rapid changes in the product development cycle, and (4) all employees are engaged in a continuous product and process improvement.

The search for alternative methodologies for the design and fabrication of moulds, for short runs of plastic components, nowadays has a great industrial demand, possible through the use of both rapid tooling technologies and new and different materials for the moulding inserts.

The idea of building moulds with moulding inserts, fabricated either in alternative metallic materials or in synthetic materials is the basis for the hybrid-mould concept (Figure 1), which can have a significant impact in the mouldmaking industry. This concept was investigated under a research project, named *Hibridmolde*, supported by the Portuguese Agency for Innovation. This project involved the Polytechnic Institute of Leiria (Department of Mechanical Engineering), the University of Minho (Department of Polymer Engineering), the CENTIMFE (Technological Centre for Mouldmaking) and Moliporex a mouldmaking company.

This project had several objectives:

- to investigate the use of distinct rapid tooling approaches to produce inserts for hybrid-moulds
- to investigate the structural and thermal behaviour optimisation of hybrid-moulds
- to study the viability of existing rapid tooling technologies for hybrid-moulds
- the development of appropriate methodologies and project rules for the optimised manufacturing of hybrid-moulds

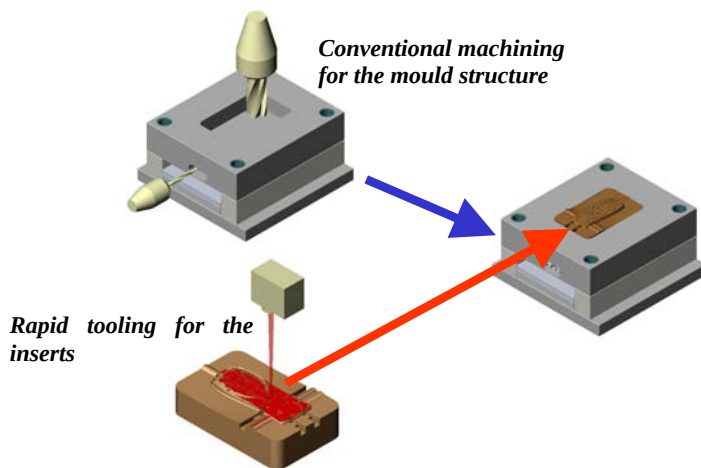


Figure 1. The hybrid-mould concept.

This paper describes the use of two rapid tooling technologies to produce inserts for hybridmoulds: epoxy tooling and selective laser sintering.

2 RAPID TOOLING

Chua *et al* (1999) describes rapid tooling technology as the technology that adopts rapid prototyping techniques to tool and die making.

There are two approaches for rapid tooling (Figure 2): the indirect approach that uses rapid prototyping master patterns to produce moulds, and the direct approach that uses directly rapid prototyping systems to produce tooling inserts (Rosochowski and Matuszak 2000, Chua *et al* 1999). Tools for short manufacturing runs are known as soft tools, while tools for longer manufacturing are known as hard tools.

2.1 Epoxy tooling

This process, also called as aluminium-filled epoxy tooling, composite tooling or cast resin tooling is a process for tooling manufacturing using an epoxy resin as the tool material.

A model pattern is prepared onto a model board to define the negative of the first half of the tool. Epoxy resin reinforced with aluminium is then cast onto the pattern directly into a supporting frame, and cured. The process is repeated for the second half of the mould. When both halves have been cast and cured, the tool can then be split and prepared for moulding. Ejectors and runners are typically milled into the tool to ensure total functionality, and the tool support frames are integrated into a mould base for assembly onto the moulding machine.

Figure 2. Classification of rapid tooling technologies.

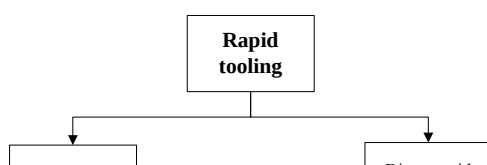
The cost of this process is typically less than 40% of the conventional prototype tooling cost, typical lead-times lie between two and four weeks and fine detail, such as graining or print, can easily be reproduced. However, flash can occur more often than with conventional tooling, leading to an increased effort in trimming the mouldings.

2.2 Selective laser sintering

Selective laser sintering (SLS) uses a high-power laser to selectively heat powder material just beyond its melting point (Dimov *et al* 2001). The laser traces the shape of each cross-section of the model to be built, sintering powder into a thin layer. It also supplies energy, which not only fuses neighbouring powder particles but bonds each new layer to those previously sintered. The sintering takes place into a sealed heated chamber at a temperature near the powder melting point, and is filled with an inert gas to reduce oxidation of the powder being sintered. Maintaining the hot environment in the build chamber also reduces both the power required from the laser and the thermal shrinkage of the model.

After each new layer is solidified, the piston over which the model is built retracts to a new position and a new layer of powder is supplied. The powder that remains unaffected by the laser acts as a natural support for the model and remains in place until the model is complete. After all the layers have been defined, the non-sintered powder is discarded to reveal the solid object formed inside. Commercial machines differ in: the way the powder is deposited (roller or scraper), the atmosphere (argon or nitrogen) and the type of laser they use (fibre, CO₂ or Nd:YAG laser).

The building cycle consists of three main stages:



- Warm up – the chamber is filled with inert gas and both the chamber and feed material are warmed up
- Part build
- Cool down – the chamber is returned to ambient temperature in a controlled way.

There are two types of SLS processes (Majewski and Hopkinson 2004, Kruth *et al* 2003, Simchi *et al* 2003): indirect and direct processes. In the indirect one, low temperature polymers are used as binders. The polymer binders are either mixed with the primary powder at a high melting temperature or coated on the surface of the primary powder. The direct SLS process involves the direct melting and consolidation of selected regions of the powder bed. Direct SLS enables to produce high or full density parts.

Many types of materials, such as polyamide (PA), polystyrene (PS), polycarbonate (PC), acrylonitrile butadiene styrene (ABS), metals, ceramics and composites can be used in laser sintering applications.

3 EXPERIMENTAL WORK

3.1 Part design

The front panel of a cell phone, indicated in Figure 3 was chosen as a case study. This part was selected due to its shape and geometrical features, which pose some difficulties with respect to the moulds' insert fabrication. The front panel has numerous holes in the front face and extensive vertical ribs in the back. Its nominal thickness is 1,5 mm and the total volume is 11,47 cm³.

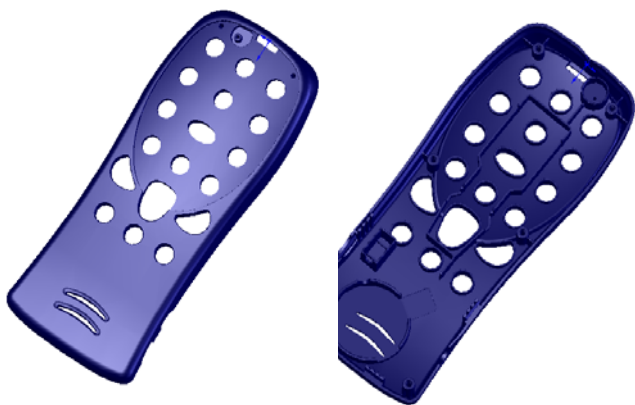


Figure 3. The front panel of a cell phone selected as case study

3.2 Mould fabrication

Moulding inserts were fabricated using epoxy tooling and laser sintering.

Figure 4 and 5 show, respectively, both the ejection and cooling systems considered on this work.

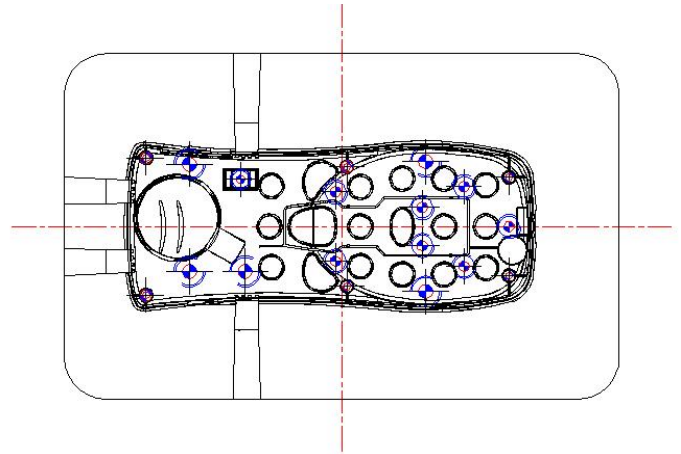
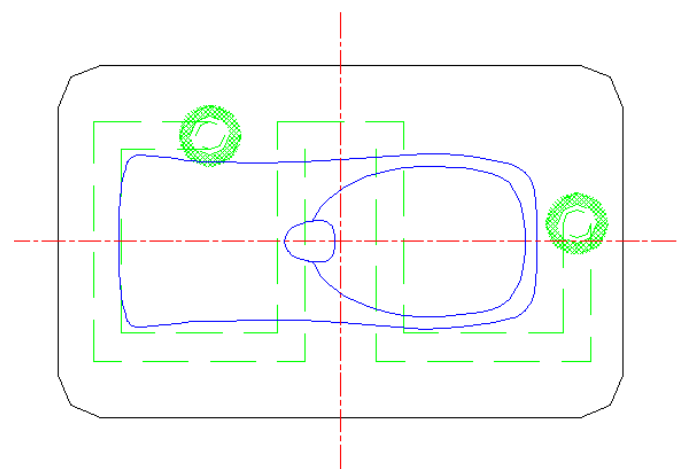
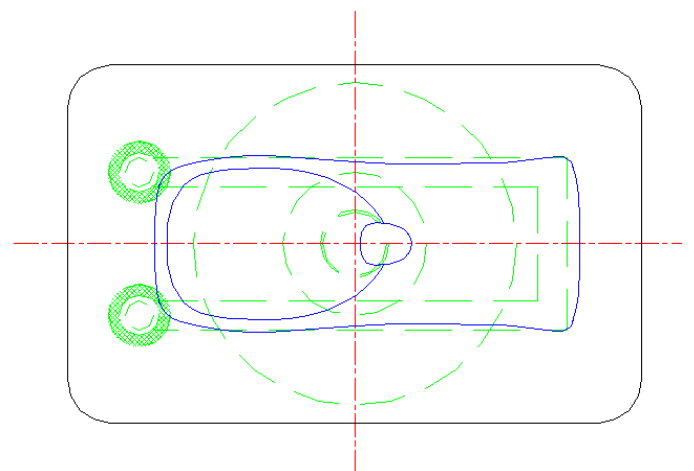


Figure 4. Position of the ejectors.



a)



b)

Figure 5. Position of the cooling channels for a) core and b) cavity.

• Epoxy tooling

Stereolithography was used to fabricate the master pattern. The SLA250 stereolithography system (3D Systems) was used with a SL## epoxy photocurable resin. After fabrication, the model was sub-

jected to several post-processing operations like support removal and post-curing, to fully solidify the model this way increasing its mechanical properties.

Mould inserts (Figure 6) were made using Neukadur VG SP 5 from Sika and the procedure previously described. The resin was cured during 4 hours at 70 °C.

Due to processing limitations, some of the part features were suppressed, namely the larger vertical ribs on the middle of the back face, the snap fits and a big boss on the top of the back face (Figure 7). Table 1 shows the main properties of Neukadur resin.



Figure 6. Core and cavity made by epoxy tooling.

Preliminary tests showed that obtaining those features was quite difficult, due to problems in separating the mould insert from the master pattern. The top edges of the bosses, corresponding to the holes in the front face of the part, were particularly degraded. In the major central boss, this was particularly evident. The surface quality was not quantified, but it could clearly be described as rough. The production of cooling channels in the blocks was also difficult.

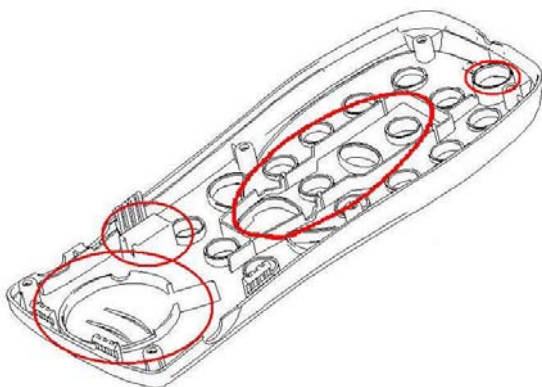


Figure 7. Suppressed geometrical patterns.

Table 1. Mechanical and thermal properties of Neukadur VG SP 5

Material properties	Values
Density	2,7 g/cm ³
Elasticity module	9.800 N/mm2
Poisson Coefficient	~0,42
Hardness	90 Shore D
Linear Expansion Coef.	30~35 10 ⁻⁶ /K
Specific heat	1300 J/kg °C
Thermal conductivity	0,7 W/mK

• Laser sintering

Inserts were produced using metallic powder Laser Form ST100 (3D Systems, USA), infiltrated with bronze, resulting in composite structures containing 40% of bronze and 60% stainless steel alloy (Figure 8).

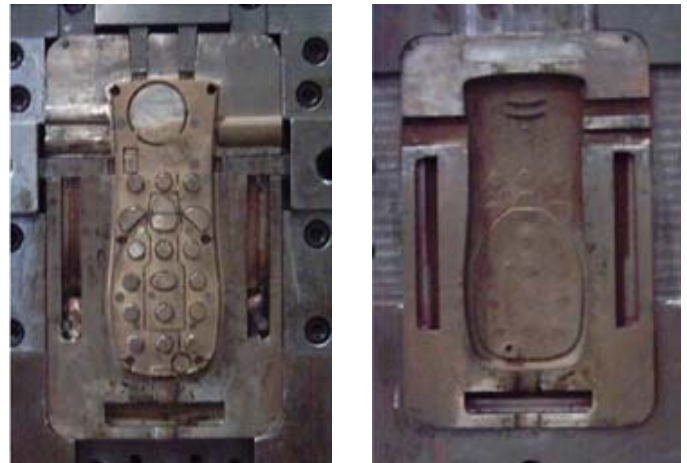


Figure 8. Core and cavity produced by selective laser sintering.

Core and cavity were identically oriented to minimize adjustment errors during the fabrication process. There was no need of part simplification.

Table 2 shows the main properties of Laser Form ST100.

Table 2. Main properties of Laser Form ST100.

Material properties	Values
Density	7,7 g/cm ³
Coefficient thermal expansion	12.4 x 10 ⁻⁶
Thermal conductivity (100°C ASTM E457)	49 W/mk
Hardness	87 Rockwell B
Young Modulus	137 GPa
Tensile-yield strength	305 MPa
Enlongation	10 %

3.3 Mould instrumentation

Produced hybridmoulds were instrumented with temperature and pressure sensors as shown in Figure 9. Due to geometric limitations related with both the water circuit and the ejection systems, an additional sensor (T1) was located in the core, just opposite to T2.

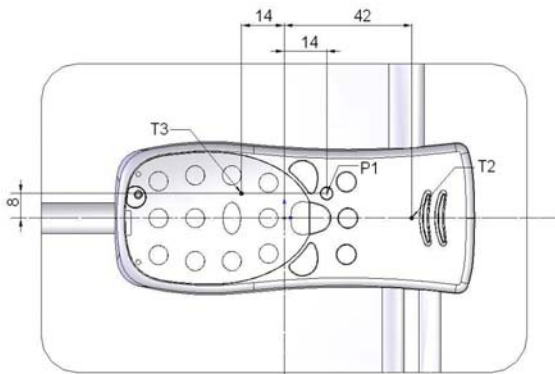


Figure 9. Sensors position within the cavity insert.

A Priamus system was used to get temperature and pressure data. Figure 10 shows the sensor signal processing system used in this research study.

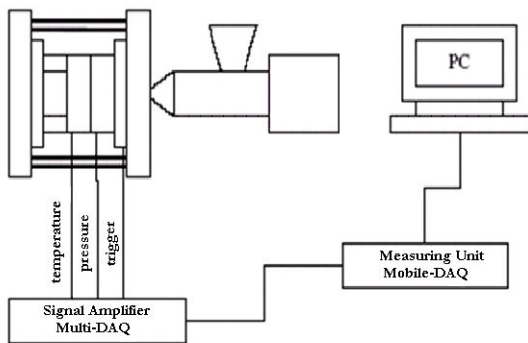


Figure 10. Sensor signal processing system.

3.4 Injection Moulding

Parts were obtained through injection moulding, using an Engel 200/45 machine with 450 kN of clamping force (Figure 11).



Figure 11. Injection moulding equipment, Engel 200/45

The material used was polypropylene, Hifax BA238 from Montel. Material data is shown in Table 3.

Table 3. Typical processing conditions of polypropylene.

Properties	Values
Density	900 Kg/m ³
Injection Temperature	180-290 °C
Mould Temperature	20-60 °C
Máx shear stress	0,26 MPa
Máx. shear rate	24001/s

Processing conditions used for both inserts made through epoxy tooling and selective laser sintering are shown in Table 4.

Table 4. Experimental injection moulding processing conditions used for both epoxy and laser sintered inserts.

Processing conditions	Resin inserts	SLS inserts
Melt temperature	265 °C	230 °C
Mould temperature	~70 °C	50 °C
Holding pressure	10 MPa	15 MPa
Holding time	10 s	10 s
Cooling time	40 s	10 s

4 RESULTS

• Epoxy tooling

Due to the thermal characteristics of the epoxy material, processing parameters are different from those conventionally used. Thus, cycle times are longer than with conventional tooling. Additionally, as a consequence of its low mechanical properties, pressure values are typically lower, which can lead to problems like sink marks. The major difficulties in establishing a suitable set up are related to the injection pressure, which should not be too high to prevent damage of the moulding block details, and the coolant temperature. The occurrence of “short shots” was frequently observed during the first tests.

Extraction was difficult, mainly owing to both the roughness of the surface and the small draft angle used. Accuracy is dependent on a multi-step process, including the accuracy of the process used to produce the pattern.

Figure 12 shows the variation of the temperature at the moulding surface. It can be observed that the temperature stabilises after 40 s and that a decrease of temperature is obtaining by increasing the distance from the gate. The higher temperature occurs at the position T3, closer to the gate, which is near 30°C, higher than at the other positions, T1 in the

core and T2 in the cavity. A 10°C temperature difference is reached between the two moulding surfaces is also evident.

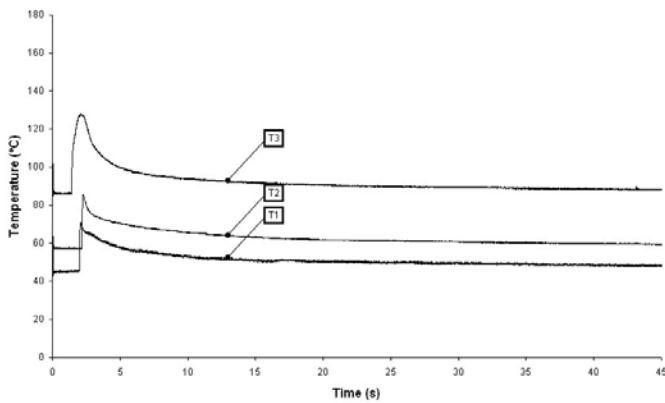


Figure 12. Temperature variation (°C) over the cycle time for the inserts made by epoxy tooling.

A low filling pressure was used. The insert degradation started after 14 cycles, when eroded pieces of the cavity insert were extracted with the injected part. The parts showed degradation, especially at the boss edges (Figure 13). Some small pits also appeared either in the core surface or in the cavity surface. In the areas of the inserts, where contact happened with the lateral movements, no evidence of wear was observed. The injection run was suspended at shot number 81.

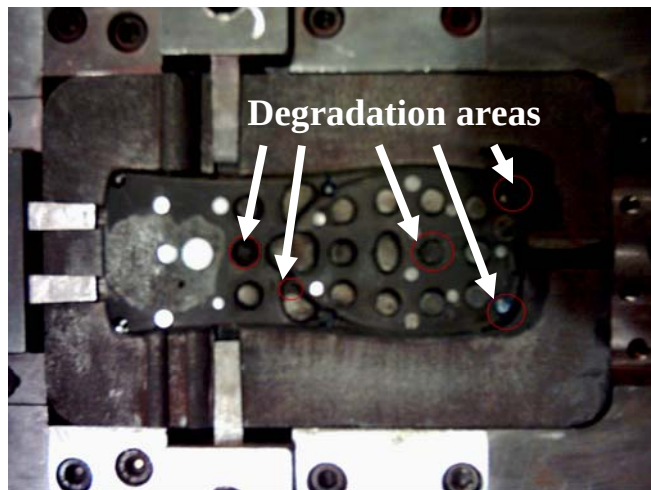


Figure 13. Degradation areas within the core made by epoxy tooling.

• Selective laser sintering

Beyond gaining in cost and time, rapid tooling also enables the creation of conformal cooling within the tooling. Conformal cooling can reduce the cycle time by 15-20% improving part quality.

However, in this case study it was too difficult to create conformal cooling channels, due to problems associated with the extraction of non-sintered powder from the internal cavity. At the infiltration stage,

the material gets consolidates and blocks the cooling circuit.

To prevent blocking of the cooling system, the inserts were constructed in two separate halves that were glued together and infiltrated. However, this solution does not enable to build the *real* conformal channels and is prone to fluid leakage during operation.

Figure 14 shows the temperature variation at mould surface, for the laser sintered inserts. Results suggest that the temperature stabilises after 20 s.

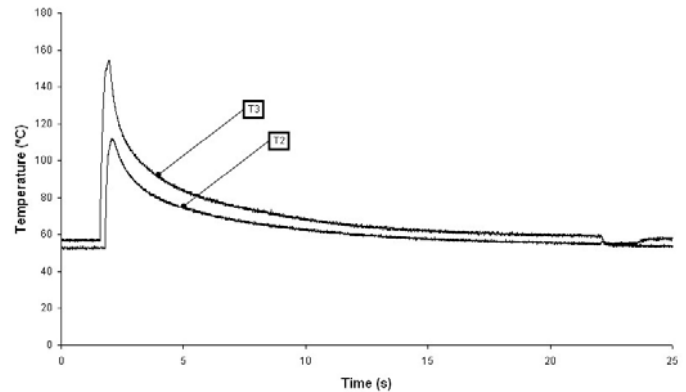


Figure 14. Temperature variation over the cycle time for laser sintered inserts.

No pressure restrictions were considered due the mechanical properties of the laser sintered inserts. Figure 15 shows the pressure variation through the cycle time. This figure enables to observe that from the instant the material reaches the pressure sensor, pressure rapidly increases to about 7MPa and slowly drops to a minimal value after 12 s. This instant of time corresponds to the onset of thickness shrinkage.

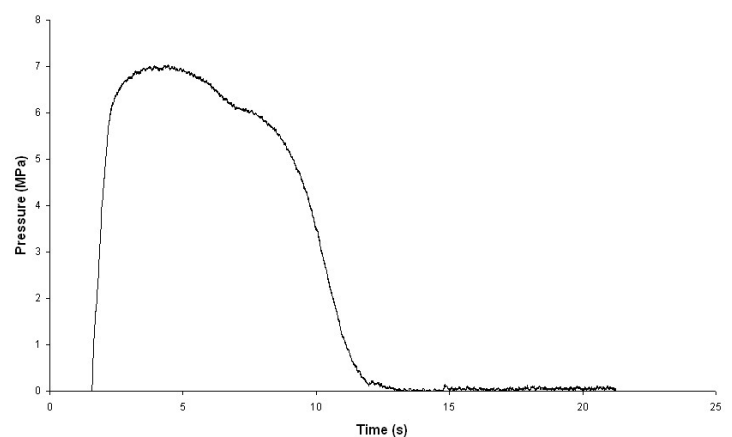


Figure 15. Pressure variation through the cycle time for selective sintered inserts.

5 CONCLUSIONS

Epoxy tooling and laser sintering were used to produce inserts for hybrid-mould produced for a complex shape.

The results suggest that moulding inserts made with the Neukadur resin are not adequate to produce parts, containing extensive ribs and deep bosses. These resins pose some problems during the preparation of moulding blocks and their fitting to the mould base. Manipulation and assembly must be carried out with particular care, as inserts are easily damaged. Injection moulding processing conditions is different from those used at conventional injection moulding. The set up of the injection process requires analysis and experimentation as it is quite different from standard moulding. Thermal properties of these inserts are key aspects of its performance. Thus, it is essential to obtain a proper cooling of the moulding blocks.

Epoxy tooling is a versatile technique to produce mould inserts of simple geometry. This rapid tooling strategy reproduces accurately small details of the master pattern. These small details will be prone to faster degradation. Therefore, epoxy tooling is more suitable to fabricate inserts with open and simple geometries.

Selective laser sintering is a direct rapid tooling technique adequate to fabricate moulding inserts, though conformal cooling channels are difficult to produce. Experimental results show that Laser Form does not affect the standard process setup. Establishing the processing set up can be followed by a similar procedure to that used for conventional moulds.

A comparison between the two techniques is provided by Table 5.

Further research is needed to evaluate the use of computer-aided engineering tools (structural and rheological tools) in order to improve hybrid-moulds design. Its main focus will be the assessment of software results through online data collection.

Acknowledgements

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Table 5. Comprision between SLS and epoxy tooling as technologies for hybrid-moulds

		SLS	Epoxy tooling
Initial information	Physical model		●
	Virtual model	●	●
Number of parts	>10.000	●	
	>1000	●	
	>100	●	●
	>10	●	●
Major dimension	<250mm	●	●
	<500mm		●
	>500mm		
Shape complexity	High	●	
	Simple	●	●
Accuracy	<0,1mm	●	
	<0,2mm	●	
	<0,5mm	●	●
Surface quality	Good		●
	Medium	●	●

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