Article:

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ABSTRACT

Purpose: This paper reports on the use of a combination of indirect selective laser sintering and machining processes to create injection mould tools, an approach designed to offer the capability to create conformal cooling channels in the core/cavity inserts together with the levels of surface finish and accuracy required to meet typical injection mould tool specifications.

Approach: The research has been pursued through three industrial case studies. In each study existing injection mold inserts have been redesigned to give a conformally cooled tool. These have then been manufactured using indirect SLS, HSM, EDM and polishing. The inserts have been evaluated in industrial trials in order to assess their performance in terms of cycle time, energy usage, durability and quality. The insights gained from the three case studies have then been developed into a series of design rules, which may be applied in the development of tooling for new applications.

Findings: The results show that significant productivity improvements and energy use reductions in injection moulding are possible through the implementation of conformal cooling, and that the material has sufficient wear resistance to be used in production applications. However, it is recommended that (i) modelling is always used to understand the impact of conformal cooling channels, and (ii) manufacture is carefully planned to ensure that the required internal geometry is created.

Originality/Value: The paper presents new results on the impact of conformal cooling on the productivity and energy efficiency of injection moulding, and on the durability of the indirect SLS material in injection moulding applications. A novel 'cut out volume' technique for powder clearing is also presented, along with a set of design rules to support further application of the work.

Keywords: tooling, layered manufacture, injection moulding, selective laser sintering, machining, powder sintering.

1. Introduction

The use of layer manufacture approaches in tooling is well established for prototype tools, which take advantage of the low lead times available from layer manufacture systems to reduce product development times, but there have been fewer applications in the field of full production tooling. A variety of approaches have been studied based on 3D printing (Xu and Sachs, 2009), electron beam melting (Rannar et al, 2007), direct metal laser sintering (Nagahanumaiah et al, 2008) and indirect selective laser sintering (SLS) (Dalgarno and Stewart, 2001a). Previous work on the creation of injection mould tools using indirect SLS identified accuracy and surface finish as significant issues to overcome (Dalgarno and Stewart, 2001b). However, the productivity benefits which can be gained from better tool thermal management using layer manufacture are substantial (Rannar et al, 2007; Xu and Sachs, 2009; Dalgarno and Stewart, 2001a), and so there is a commercial driver to address these issues.

The aim of the work reported here was to evaluate an approach which considered the layer manufacture system as a near net shape manufacture process, and used conventional finishing processes to create a net shape mould tool. The application area was injection moulding, where the tolerances and surface finish requirements are very demanding, as highly finished surfaces are needed to create industrial or consumer goods which have both functional and aesthetic reasons for needing accurate and well defined surfaces.

The approach taken has used one layer manufacture process which previous work has identified as able to create mould inserts which have the mechanical properties required, the LaserForm system from 3D Systems, with high speed machining (HSM) and electro-discharge machining (EDM) as the primary finishing process, supplemented by grinding and polishing where appropriate.

The research has been carried out through three industrial case studies, with mould inserts manufactured and trialed on industrial moulding presses in each case. Although valuable in terms of providing real industrial data on the performance of the tools, this approach did bring the constraint that the inserts produced had to conform to existing moulding systems, without the opportunity to start from scratch. This meant that (i) the existing ejector system had to be used, (ii) the location of cooling circuit entry and exit from the inserts was fixed, (iii) that the new design had to accommodate any other functional parts of the tool, and (iv) that the surface finish and tolerance as specified on the original tool should be replicated. In practice the negative impact of this constraint was far outweighed by the positive, and the case studies have also provided the opportunity to develop design rules which may be applied when considering this approach for new tooling applications.

2. Initial Studies

The processing steps for the indirect SLS route as used in the work reported here are described in full elsewhere (Ilyas, 2008), and so is only briefly presented here. The material used was LaserForm ST-100, from 3D Systems, which was supplied as a polymer coated steel powder, and which was processed on a 3D Systems Vanguard SLS System, based at the University of Leeds. Once a design had been finalised, an .stl file was generated and electronically communicated to the machine. The SLS machine then used a conventional SLS processing strategy to process the polymer coated steel powder. The SLS processing bonded the steel powders together through the binder, in order to create a "green part": in essence a 3D structure made up of steel powder held together by the polymer binder. At this stage the 3D structure is consolidated, but is surrounded by loose powder, which must be removed in order to reveal the structure. As the consolidated structure is fragile at this stage this must be completed carefully. Once the green part has been cleaned, it is transferred to an oven (in our case a Carbolite Furnace). Here the part is heated 1075ºC, and held at that temperature for four hours before cooling. During this temperature cycle three processes occur. Firstly, at a relatively low temperature, the polymer binder is burnt off and vaporized, leaving a porous metal skeleton. Secondly, as the temperature increases beyond 1000ºC the steel powder starts to sinter. Finally, at 1075ºC molten bronze is introduced to the structure and infiltrates the pores, with continued sintering and infiltration happening concurrently. Once the furnace cycle is complete the 3D structure is 60% steel/40% bronze composite material.

Previous work had identified a number of key concerns with regard to manufacturing mould tooling using the indirect SLS route. These were powder removal, precision and machining allowances, surface finish, and residual porosity (Dalgarno and Stewart, 2001b), and initial work was directed at how these concerns would be addressed.

2.1 Powder Removal

AS noted in the introduction, one of the main benefits of using a layer manufacture method is that complex shapes can be created, and of particular benefit in tooling applications is the creation of conformal cooling channels. However, with an indirect SLS approach, at the green part stage special attention has to be taken to clearing loose powder from inside the channel, as clearing complex and winding cooling channels can be time consuming (and therefore expensive). In clearing the powder inside the cooling channels, the part weight, geometry and path complexity of the channels are the main parameters that need to be considered (Dalgarno and Stewart, 2001b).

To facilitate access and accelerate powder removal, a 'cut-out volume' technique was used for clearing powder. The basic idea is that a certain volume of the green part is cut out from the main body of the inserts in order to open and bisect the cooling channel at the most difficult locations to reach in clearing the powder. After the channel has been cleared, the cut-out volume is then assembled back to its main insert before the furnace infiltration step which joins it back to the main body of the insert, effectively making the infiltration step a combined infiltration and brazing step. Figure 1 illustrates the approach, which is further illustrated in section 3.1 with reference to case study 1.

Take Figure 1 here

2.2 Precision and Machining Allowances

In order to allow for both the precision of the indirect SLS process, and to ensure that material was available to machine to a net shape, the insert geometry was altered prior to the indirect SLS stage by adding 0.5-1 mm of material to all surfaces, except the surface of the insert opposite to the tool face (the "back" face of the insert). The 1 mm value was determined on the basis of a benchmarking study (Ilyas et al, 2005; Ilyas 2008). On the basis of results from the same study special rules were created for small features. Small features are common in mould inserts, however, and small positive features are fragile and difficult to preserve in the green part stage of indirect SLS, and it can be difficult to clear powder from small negative features at the same stage. The benchmarking study identified that features with any dimension of less than 2 mm were unlikely to be produced to the level of precision required for a mould insert, and in developing the case study inserts these features were removed from the geometry to be produced by indirect SLS, and created at the finishing stage using HSM. This approach acknowledges that indirect SLS was being used within this study as a near net shape manufacturing process, with HSM and other finishing processes being used to create the net shape component.

2.3 Surface Finish

Table 1 summarises standard surface finish grades. Mould tool inserts will commonly require finishing to N0-N2 levels, whilst indirect SLS generally produces a surface finish of around 2 µm Ra, and so clearly additional finishing is required in order to produce components to specification. The approach taken here has been to use HSM as the primary finishing method, primarily as it is an automated approach. With appropriate machining parameters this can give a surface finish at an N3 level. Where a better finish than this was required, traditional mould polishing techniques were used. In some cases, most notably deep or narrow slots, HSM was unable to access surfaces which required finishing, and in these cases electro-discharge machining (EDM) was used.

Take Table 1 here

2.4 Porosity

Our general experience has been that there is little or no residual interconnected porosity in indirect SLS parts. However, in order to ensure that this was not a problem during the case studies, parts were resin impregnated after the furnace infiltration step. The sealant used was Ultraseal PC504/66, a methacrylate, and this was vacuum infiltrated.

3. Case Studies

3.1 Case Study 1 (CS1)

A snap-on tube top, shown in Figure 2, formed the first case study. The closure was of approximately 50 mm diameter, is produced in polypropylene, and requires a glossy finish all over, typical of a consumer goods product. The average production volume for this product is approximately 100,000 to 200,000 products per year, with an average product life of 5 years. The total cycle and cooling time to mould this product using the existing mould insert were 14.1 s and 7.0 s respectively.

Take Figure 2 here.

3.1.1 Insert Redesign

Figure 3 shows that the existing tool contains a number of inserted components (201, 300, 302, 303, 305, 307 and 308). From these components, the main body of both top (300) and bottom (307) insert, cap insert (302), hinge insert (303) and rib insert (308) were selected to be manufactured by SLS. In order to allow for a better cooling system inside the inserts, both top and bottom inserts were redesigned by merging as many as possible of the inserted components into one solid component. However, machining and finishing were major design constraints. From the original inserts, it was identified that there are deep slots on the rib inserts, surface textures on the hinge, and undercuts for lid lock which required EDM finishing. Since a glossy finish of the product external and major internal surfaces was required, most surfaces that formed the mould cavity required a polished quality surface finish.

Take Figure 3 here

For the new top insert (Figure 4 (a)), the cap (302) and hinge (303) components were selected to be merged to the main body in order to provide more options in constructing conformal cooling channels. From a manufacturing perspective, merging both 302 and 303 allows the tightest tolerances for fitting to be removed, and reduces significant numbers of surfaces to be machined. For components 201, 305, and 312, the existing components were used, with the decision based on manufacturing constraints, and the use of interchangeable and moving parts.

Take Figure 4 here

For the new bottom inserts (Figure 4(b)), a design involving two separate plates was adopted primarily due to the requirement of a polished quality surface finish on both external and internal surfaces that form a rib insert. The two plate design made these two surfaces accessible for polishing.

Internal to the inserts, conventional straight-drilled cooling channels were replaced by conformal cooling channels. Figure 5 shows the original and new cooling channel designs.

Take Figure 5 here.

Both the channel diameter and distance between the cavity surfaces and cooling channel centre line and between adjacent channels were maintained at 8 mm where possible, based on previous experience (Dalgarno and Stewart, 2001b). To increase the cooling area, the channels have been made serpentine where geometry allowed. Where channels ran from one plate to another on the bottom insert they were sealed by o-rings.

3.1.2 Design for Manufacture

Following the logic outlined in section 2.2, all small/delicate features, deep narrow slots, and drilled holes on the new inserts were added and finished later by high speed machining, EDM, and polishing. A 0.5 mm machining allowance was then added to all surfaces. Figure 6 shows the post-processing operations applied to the top insert.

Take Figure 6 here.

The top insert was produced using the "cut-out volume" approach described in section 2.?. Figure 7 shows how the near net shape CAD was split in order to provide an effective and efficient approach in clearing the loose powder from the channels, and shows how the green parts were assembled.

Take Figure 7 here.

3.1.3 Manufacture

Figure 8 shows the inserts at various stages through the manufacturing process. Prior to machining the inserts were sealed as described in section 2.4. In addition to the machining operations, illustrated for the top insert in Figure 6, all surfaces that formed the mould cavity were polished to 0.02 μm Ra.

Take Figure 8 here.

3.1.4 Moulding Trial

A moulding trial with the redesigned inserts was run in the production workshop of Seaquist Closures Ltd. in Leeds using a Kloeckner Ferromatik FM-85 injection machine, and polypropylene as the moulding material. The moulding parameters for running the inserts were initially set up as per the operating parameters as the original inserts, with a cycle time of 14.1 seconds used for the first two hours, and the moulding cycle time was then reduced incrementally. The cycle time was reduced every 2 hours of running as follows: 5% (13.4s), 15% (12s) and 20% (11.3s). The cycle time reduction could not be continued further because the machine mechanism could not keep up with the cooling cycle (the "machine limit" had been hit).

Machine energy consumptions for each cycle time were monitored and measured using equipment developed at the Univesity of Bradford (Dawson et al, 2004). The equipment measures power consumption from the machine junction box. At 5%, 15% and 20% cycle time reductions, the machine energy consumption fell by approximately 4% (to 119 kJ/part), 10% (112 kJ/part) and 13% (108 kJ/part) respectively.

Samples for each cycle time were collected for quality inspection. Company standard procedures for quality inspection were used. Parts produced at the 11.3s cycle time did not meet quality standards, showing significant distortion, and this cooling time was considered to short to allow parts to freeze sufficiently before ejection. Parts produced at the 12s cycle time did not exhibit this effect, and met specification.

Durability of the tool was assessed by running the machine at the 12s cycle time to produce 25,000 mouldings in a single uninterrupted trial. Twenty samples were taken just after the moulding process reached its steady state. Then, consecutive batches of twenty moulding were taken every 1000 mouldings, and in addition a range of key dimensions on the inserts were measured before and after the trial, as illustrated for the moving half of the tool in Figure 9. The only measured dimension which showed a significant change was diameter 'O' in Figure 9, which reduced from 46.22mm to 45.79mm.

Take Figure 9 here.

Figure 10 shows the variation of dimension 'O' measured on the mouldings produced throughout the trial, based on the average of the twenty mouldings sampled at each point. Variance? The negative slope implies that the impact of the tool wear on the mouldings is a reduction in diameter of 0.0013 mm per 1000 shots. As the tolerance on this dimension was ± 0.2mm, this gives a maximum possible tool life of just over 300,000 shots, assuming that the tool could be manufactured close to the upper tolerance limit. Surface roughness measurements on the tool indicated no significant change over the course of the trial (0.02 μm Ra before, 0.018 μm Ra after).

Take Figure 10 here.

3.2 Case Study 2 (CS2)

The second case study considered a receptacle spoke (Figure 11) from Trisport Ltd. The production volume for this product was 40 million per year using a 16 cavity mould. With an average product life of 2 to 5 years, mould inserts were designed to be able to deliver 5 to 12.5 million shots. The required cycle and cooling time to mould this product using the existing mould insert were 8.0 s and 2.5 s respectively. The closure was approximately 22 mm diameter and 6 mm thick, and was produced in a polyamide material.

Take Figure 11 here

3.2.1 Insert Redesign

The redesign of the inserts again focused on modification of the cooling channel design. Figure 12 shows the original and redesigned inserts. The original inserts had the cooling channels for both moving and fixed inserts externally constructed as turned grooves located approximately 9 mm from the cavity. The redesigned inserts were constructed inside the inserts and laid out conformal to the cavity. The revised cooling channels were approximately 4 mm from the cavity.

Take Figure 12 here

3.2.2 Design for Manufacture

The inserts contained a large number of small features, which it was decided would be added by HSM/EDM. The new moving and fixed inserts were therefore designed as simple cylinders with conformal cooling channels constructed inside them. A 1mm machining allowance was added to all external dimensions to provide stock for machining/finishing. Figure 13 shows CAD images of the redesigned inserts.

Take Figure 13 here

3.2.3 Manufacture

Figure 14 shows the near net shape inserts after infiltration. Sixteen sets of moving and fixed inserts were developed. No special treatment was taken for powder clearing as the cooling channels were not complex. To finish the inserts to production specification turning, cyclindrical grinding, HSM and EDM were all employed.

Take Figure 14 here

3.2.4 Moulding Trial

The moulding trial was run at the Trisport production workshop, in Tamworth, UK. As in CS1, the moulding trial progressed by reducing the cycle time gradually. At the beginning of the trial, the moulding process was warmed up for about an hour at the optimum production cycle time of the original inserts (7.7s) until process steady state was reached. Cycle time reduction was then carried out with the following reductions, each after one hour of running at a steady state: 4% (7.4s), 8% (7.1s), 12% (6.8s) until reaching the machine limits of 16% (6.5s). However, subsequent testing demonstrated that the original inserts could also operate at the 6.5 s cycle time. Dimensional analysis of receptacles produced by both the conformal and conventional tools showed equally acceptable performance.

3.3 Case Study 3 (CS3)

Case study 3 focused on a polypropylene closure from Unilever Ltd, shown in Figure 15, with dimensions of approximately 40 x 60 x 30 mm. The existing mould for this component ran with a cycle time of 15 seconds using 24 cavities. The average production volume per year from this mould was between 24 and 48 million mouldings, with an expected product life of 3 years.

Take Figure 15 here

3.3.1 Insert Redesign

Figure 16 shows the two core and cavity inserts which were the focus of the tool redesign, and the external geometry of the inserts was kept the same in order that the inserts could be evaluated within an existing tool. For this case study, an analysis of moulding performance of the cooling channels was carried out by running a filling/packing and cooling simulation using the Moldex3D analysis software (ref). Figure 17 shows the cooling channel design which resulted from the analysis, and Table 2 shows the predicted cooling time/temperature profiles from the existing and proposed designs. Use of the Moldex3D software also allowed analysis of the relative contributions of the material (which contains copper as so will have a greater thermal conductivity), and new cooling channel designs to the cycle time reduction, and attributed 80% of the cycle time reduction to the changed cooling channel design (Ilyas, 2008).

Take Figures 16 and 17, and Table 2 here

3.3.2 Design for Manufacture

Near-net shape designs of the redesigned cavity and core inserts for indirect SLS process were first generated, with, as before, small features removed, to be produced later using HSM and EDM. A general machining allowance of 1mm was applied to most surfaces, with a larger 2mm allowance was applied to the horizontal surfaces of the cavity inserts to allow for larger furnace deformation due to the large part volume (green part weight 5kg). For powder clearing from the channels, conical 'cut-out volumes' at several selected locations were prepared on both inserts at green-part stage, as indicated in Figure 18. Green part 'plugs' for these holes were also created, and were used to seal the 'cut-out' volumes at the infiltration stage, using the same combined infiltration/brazing approach as outlined for case study 1.

Take Figure 18 here

3.3.3 Manufacture

Figure 19 shows the green parts of the inserts prior to infiltration, and Figure 20 shows the finished inserts. To achieve final production specifications, milling, drilling, HSM, EDM and polishing operations were required, with a 0.1μm surface roughness (Ra) on the moulding cavity achieved.

Take Figures 19 and 20 here

3.3.4 Moulding Trial

The moulding trial for the case study 3 inserts was run on the same injection moulding machine as used in case study 1. As with the two previous case studies, the productivity of the new CS3 inserts were investigated by reducing the cooling and cycle time gradually. To reach process steady state, the mould was first run for about an hour at the conventional production cooling (4.7s) and cycle (9.9s) times, and the cooling time was reduced to 4, 3, 2 and 1 s progressively. Product samples were taken at each cycle time for inspection, and parts from all cycle times met the product specification. The reduction in energy consumption per cycle from the original cycle time to the lowest cycle time was 26 kJ, from a starting point of 130 kJ.

4. Discussion

4.1 Case Study Review

The three case studies have demonstrated that inserts produced using the indirect SLS approach can be finished to the required specification, are durable, and produce moldings which are to specification. Table 3 summaries the productivity and energy improvements gained in each case study, which taken on average (25% productivity improvement, 11% energy saving) are impressive. However, as case study 2 demonstrates the approach does not necessarily translate to cycle time benefits for all tools, and we consider that the part used in case study 2 was not sufficiently large or complex in shape to take best advantage of what conformal cooling has to offer. It should be noted, however, that both the original tool and conformal inserts were operating at the machine limit in terms of cycle time – it is possible that the conformal inserts would have shown an advantage had the machine been able to run at a lower cycle time. It is also clear that conformal cooling offers significant benefits where it is applied correctly. We believe that case study 3 has demonstrated the value of up front simulation in determining whether or not to apply conformal cooling in a particular tool design.

The ultimate test of whether or not a particular manufacturing process chain should be chosen is economic. For the three case studies we have outlined here initial cost modelling has indicated that for case studies 1 and 3 use of the conformal inserts would be economic for a wide range of required production volumes (up to around 1 million parts per insert required), with an assumed insert durability of 300,000 shots (as indicated from the wear trial in case study 1). The tool manufacture cost is marginal when set against long term running costs, and the improved productivity offsets the predicted cost of having to replace inserts. To go beyond this would require a more durable tool – our models indicated that with a durability of 500,000 shots the conformal inserts would be more economic for all production volumes of the case study 1 and 3 parts. Extrapolating from the case studies to give a general rule is difficult, as tool wear is sensitive to the material being injected and core/cavity geometry, but it is clear that for a wide range of moulding applications the approach used here would provide an economic solution. The lack of a well proven model of tool wear in injection moulding makes prediction to a finer degree impossible at the moment, and the decision is one which requires both experience in injection moulding for long production runs, and a good appreciation of the possibilities layer manufacture methods offer. Clearly any material developments in the indirect SLS approach (whether in the material itself or in coating technology) which helped to create tools with even greater durability would be of benefit in this application.

The case studies have also indicated two technical points of note. The first of these comes from case study 1, and is the observation that through using a layer manufacture method it was possible to merge parts together, significantly simplifying the tool. The second comes from case study 3, where the use of Moldex3D has allowed us to show for that case study that the cycle time benefits are attributable primarily to improved cooling channel design, with the change in material thermal conductivity a secondary effect.

4.2 Design Rules

Through the case studies we have developed a procedure for the design and manufacture of tooling using indirect SLS and machining processes, and this is outlined in Table 4. Much of stages 1 and 2 in the table is common to any injection mould tool design project, and there is a wide range of literature to support that activity (e.g. Rosato and Rosato, 2001; Michaeli et al, 2001). For the selection and positioning of cooling channels we would recommend that injection moulding analysis software be used, whether that be the Moldex3D software used by us in case study 3 or an alternative software product which allows analysis of the cooling phase of the cycle. We have found the minimum practical channel size to be around 6 mm, and in general did not position channels closer than a channel diameter to the insert surface or to any other feature. Within those constraints we strove to position channels as close to the cavity wall as possible, and to provide a maximum surface area to achieve uniform cooling. We consider it possible for optimisation routines to be developed which will follow these rules, and may pursue this in future work.

At stage 3, machining allowances must be applied. A 1 mm machining allowance, plus addition of any material required to provide for workholding during machining steps, plus the removal of any small features (typically any feature with a dimension of less than 2 mm) which can be more easily produced using either high speed machining or EDM. In addition, the necessity for 'cut-out volumes' should be assessed at this stage. Our experience has been that these do provide for much easier powder clearing and save significant time in developing parts. We would recommend the use of a cut-out volume where powder will be left more than 15 diameters away from an exit point, or if it will be separated from an exit point by the channel bending by greater than a 90º angle. Figure 21 gives recommended draft angles and feature dimensions for cut-out volumes.

Take Figure 21 here.

Stage 4 brings the various decisions taken together through the development of a an overall process plan for the development. Here we would recommend that staged CAD descriptions are available (showing green part, infiltrated part, and finished part), and that the finished part CAD shows clearly what finish should be applied to which surfaces (as Figure 6 did for case study 1).

4.3 Wider Implications for Application of Layer Manufacture

The use of the 'cut out volume' approach in easing powder clearing increases the range of practical geometries which can be created using the indirect SLS technique, and has broad potential applicability for indirect SLS in other applications, and for other layer manufacture processes which have a heat treatment stage, such as the ExtrudeHone approach which creates green parts through the 3D printing route, and the design rules outlined above (or a variant of them) could have value in developing such approaches.

4.4 Implications for Other Metal Layer Manufacture Approaches for Tooling

There are a range of direct metal layer manufacture approaches now available on the market, which would also be able to create conformally cooled tool inserts. A range of materials are available, some of which are likely to be more resistant to tool wear than the LaserForm material. None of the current approaches offers the ability to generate the precision and surface finish generally required for tooling applications, and so the combined layer manufacturing/machining approach outlined in this paper would also be relevant to the application of those techniques for injection mould tooling. The authors also consider that the use of cost and performance modeling techniques at the design stage to seek more optimum solutions would be of great benefit in both choosing a layer manufacture technique and in the design of the insert itself.

5 Conclusions

1. The case studies have shown that using indirect SLS with machining and polishing techniques can create high performance mould tool inserts for injection moulding. The inserts have demonstrated the capability to offer productivity improvements and reductions in energy usage, but these benefits cannot be assumed to apply in all applications. The use of cost and performance modeling is recommended to evaluate benefits on a case by case basis.
2. The cut-out volume technique has been shown to be very useful for the manufacture of complex internal geometries in powder based layer manufacture techniques which have a furnace sintering stage.

3. Careful process planning is required to support the use of machining processes for finishing, and the cut-out volume technique.

6. Acknowledgments

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Classes	Ra (µm)	Surface Requirements	Manufacturing Method
N0 – N2	≤ 0.05	High gloss, no visible scratches or flow line	Lapping; Polishing
N3	0.1	Glossy, small visible scratches acceptable	Polishing; Grinding; Honing; HSM
N4	0.2	"Technical" finish	Milling; Drilling; EDM
N5	0.8	No aesthetical requirements	Sand blasting

Table 1 - List of Standard Surface Finishes (ISO, 2002)

Design	Cooling Time (s)	Min Surface Temp. (°C)	Max Surface Temp. (°C)
Existing Insert	5	20.2	83.8
New Insert	5	15.9	64.6
	4	16.4	70.7
	3	17.1	77.6
	2	17.9	84.0
	1	18.1	85.8

Table 2 – Case Study 3 Predicted Surface Temperatures (Ilyas, 2008)

Case Study	Original Tool Cycle Time (s)	Cycle Time with Conformal Inserts (s)	% improvement in productivity	Energy used per moulding with original tool (kJ/part)	Energy used per moulding with conformal inserts (kJ/part)	% reduction in energy use per part
1	14.1	12	17	124	108	13
2	6.5	6.5	0	9	9	0
3	9.9	6.2	59	130	104	20

Table 3 Summary of Case Study Results

Stage	Description	Activities
1	Product Review	▪ Part specification review ▪ Selection of parting line, gate location(s), and ejection system
2	Net Shape Insert Design	▪ Tool design to identify core and cavity inserts ▪ Specification of component parts of tool, including core and cavity inserts, incorporating cooling system design
3	Near-Net Shape Insert Design	▪ Application of machining allowances ▪ Identification of small features to be removed from the near-net shape insert, plus addition of any additional material as a result of this ▪ Identification and design of any required 'cut-out' volumes ▪ Addition of tabs from infiltration
4	Manufacture Planning	▪ Process plan and staged drawings ▪ Guidance for machining/finishing

Table 4 – Tool Design and Manufacture Procedure

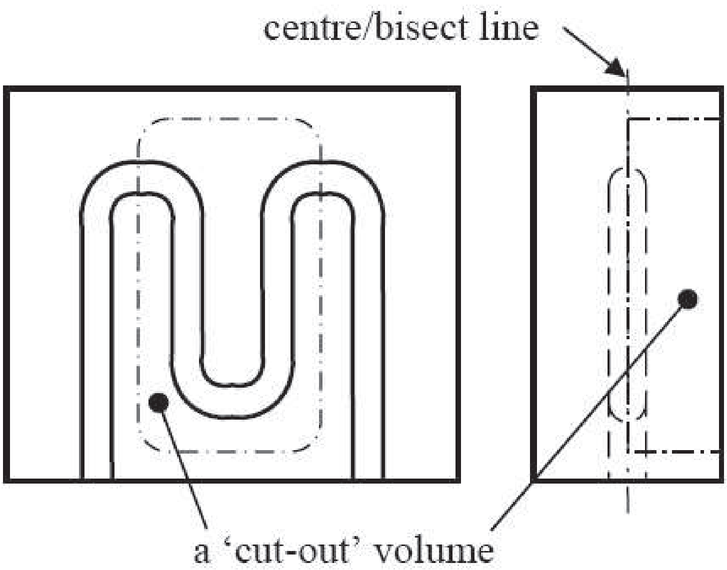
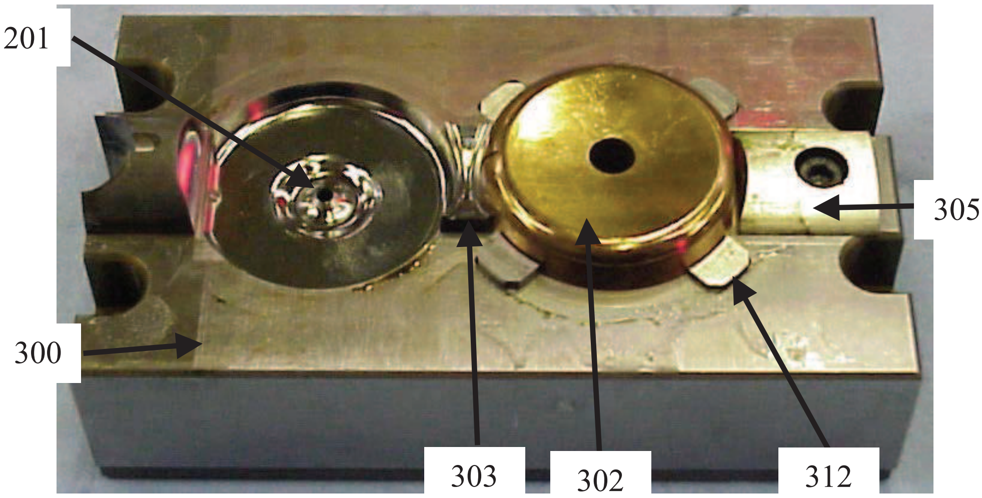


Figure 1 – Illustration of 'Cut-Out Volume'

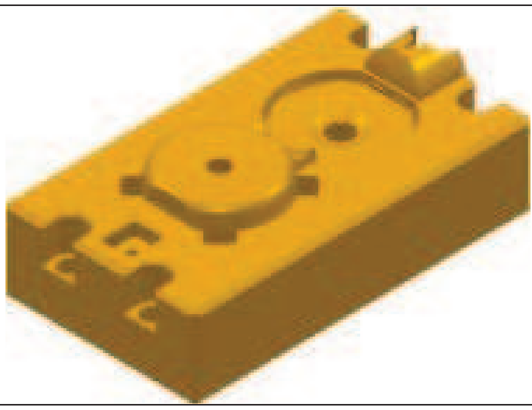
Figure 2 – Closure Product for Case Study 1



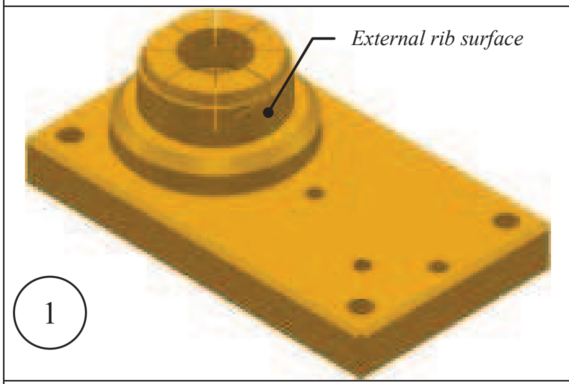
(a) Top Insert

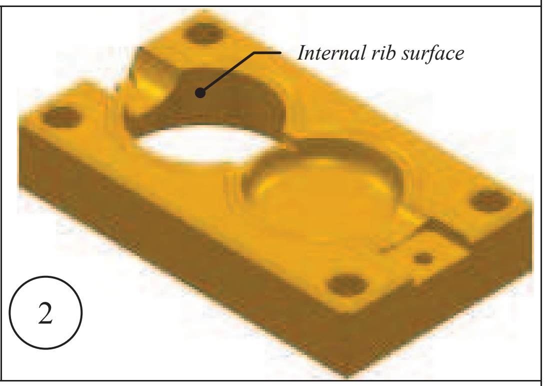
(b) Bottom Insert

Figure 3 – Case Study 1 Original Insert Assembly



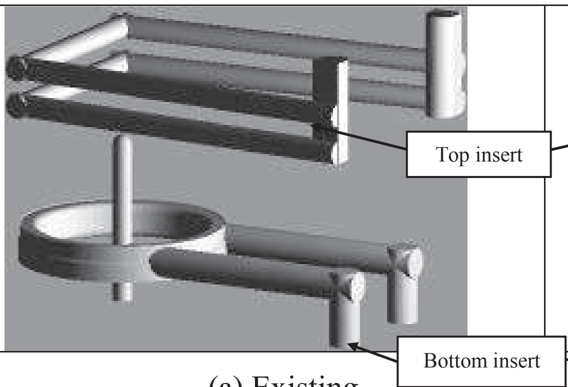
(a) Top Insert

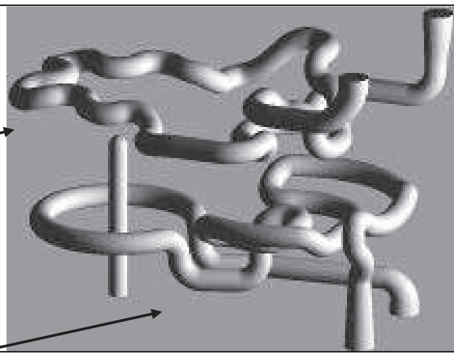




(b) Bottom Inserts

Figure 4 – Redesigned Case Study 1 Inserts





(a) Existing

(b) New

Figure 5 - Cooling Channels: Existing vs. New Mould Inserts

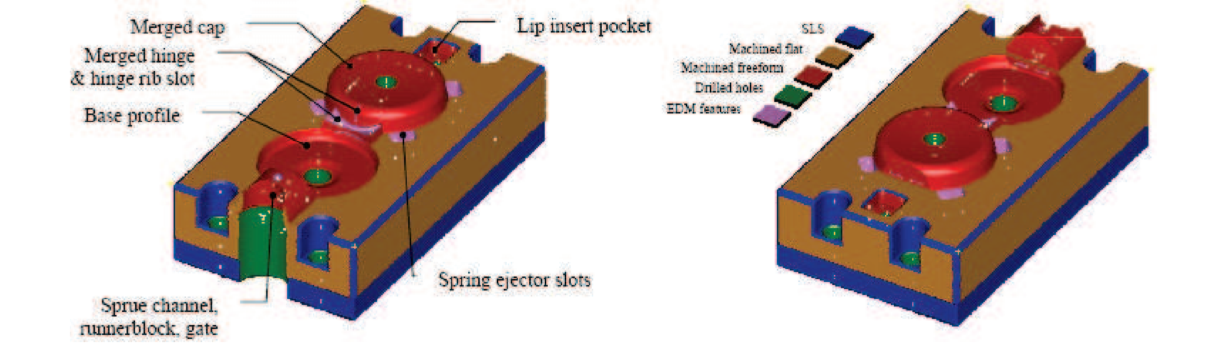
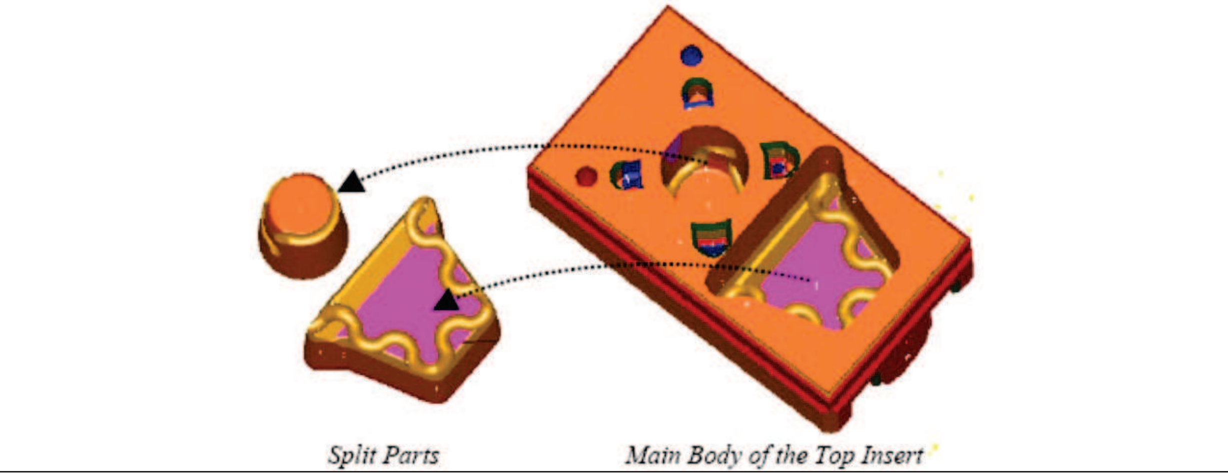
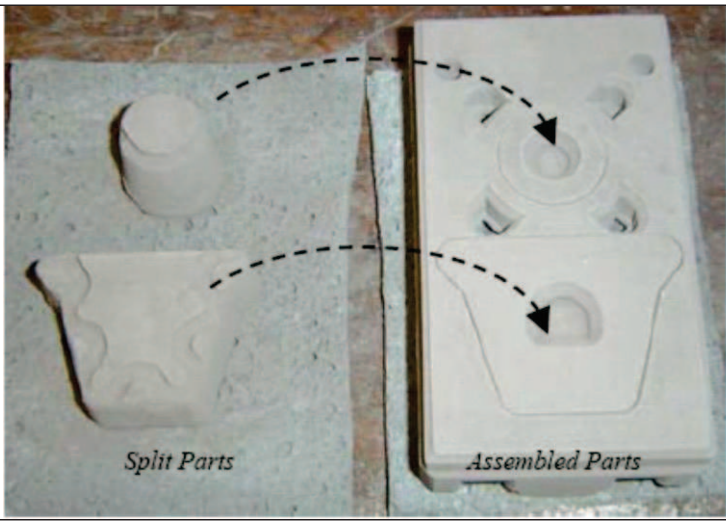


Figure 6 - Manufacturing Operations of the Top Insert



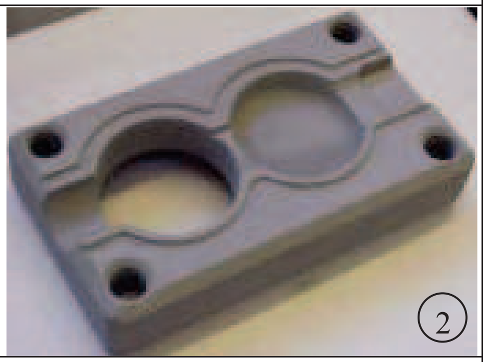
(a) 3D CAD of Split Model



(b) Split and Assembled Green-Part

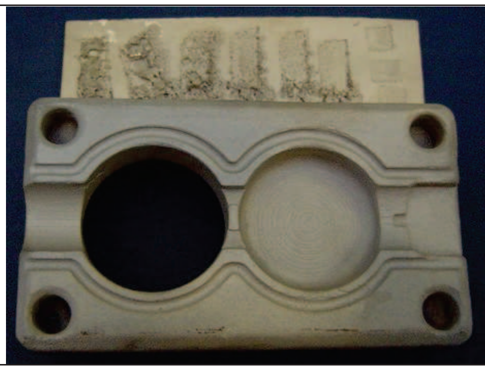
Figure 7 – ‘Cut-Out Volumes for Redesigned Case Study Top Insert

(a) Green Part Top Insert



(b) Green Part Bottom Inserts

(c) Top Insert After Infiltration



(d) Bottom Insert After Infiltration

Figure 8 – Case Study 1 Inserts During Manufacture

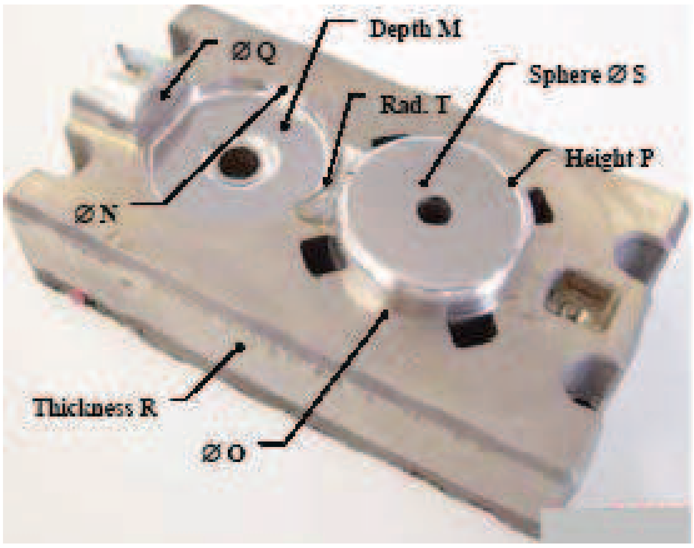


Figure 9 – Dimensions Monitored in Durability Trial on Top Insert

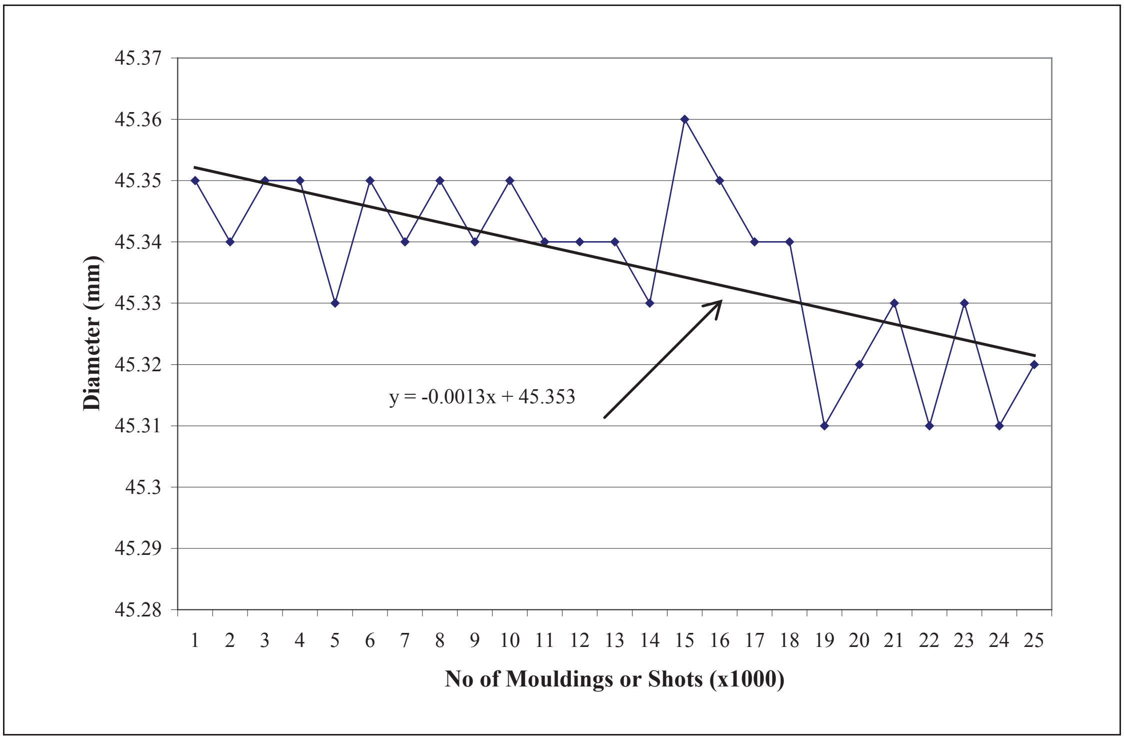
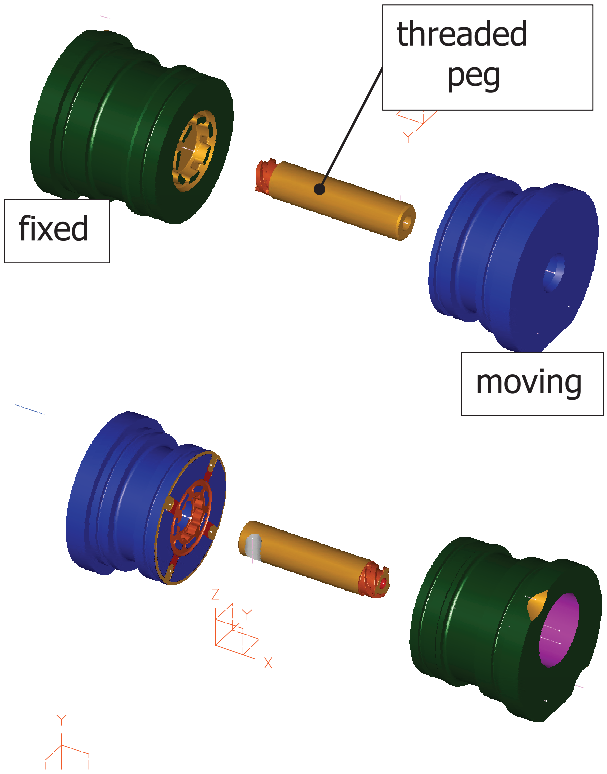
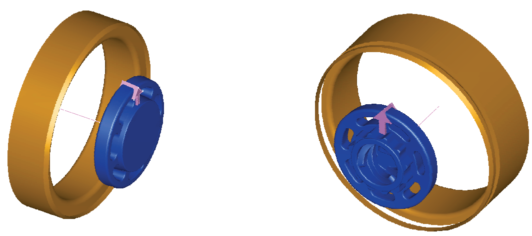


Figure 10 – Variation of Dimension O (from Figure 9) Through Durability Trial

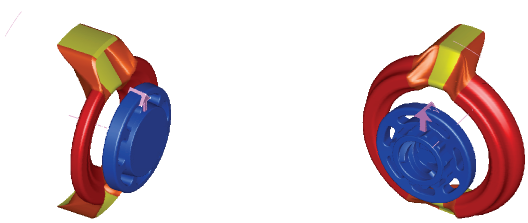
Figure 11 – Case Study 2 Component



(a) CS2 Original Inserts



(b) CAD Showing Moulding in Blue, Original Cooling Channel in Gold



(c) CAD Showing Moulding in Blue, Redesigned Cooling Channel in Red/Gold

Figure 12

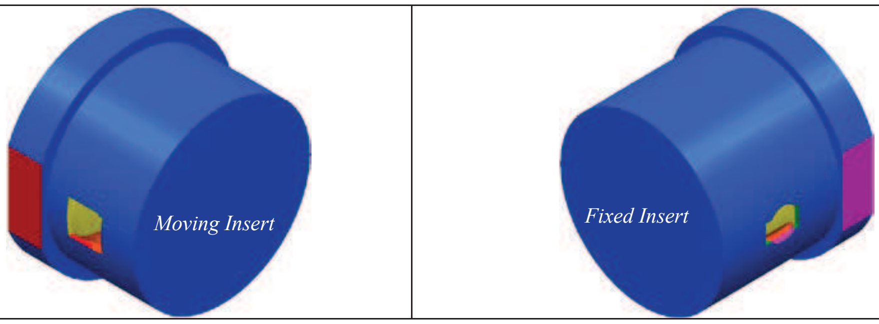


Figure 13 – CS2 3D CAD Models

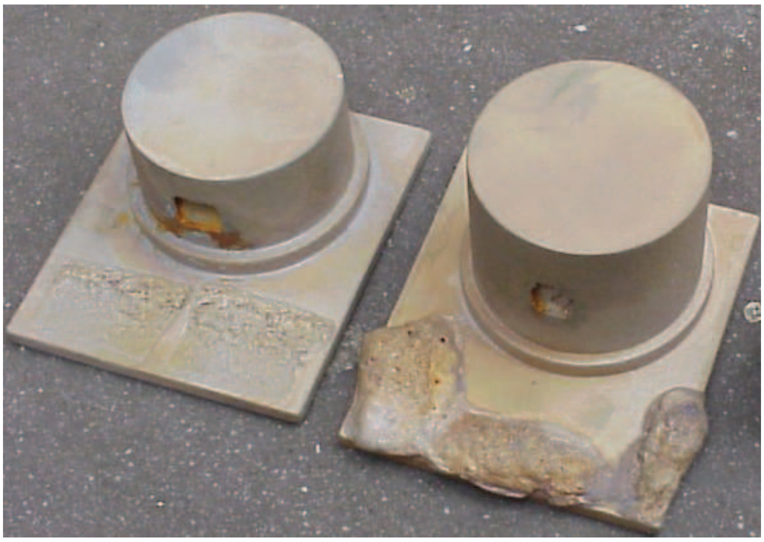


Figure 14 – CS2 Infiltrated Parts

Figure 15 – CS3 Moulding

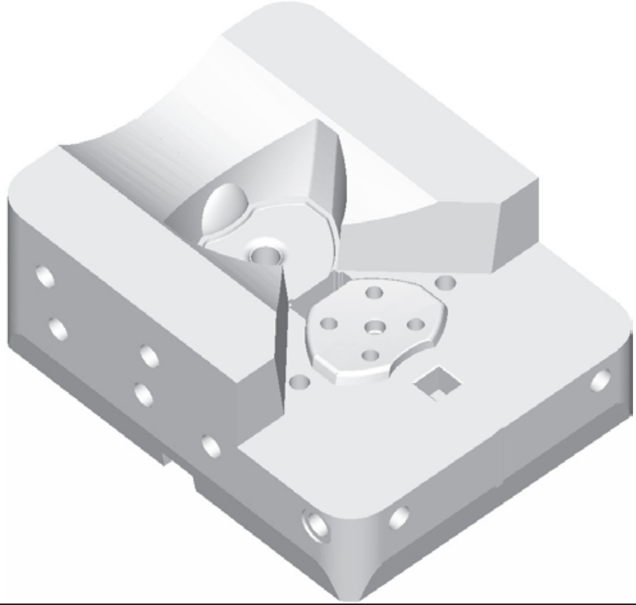
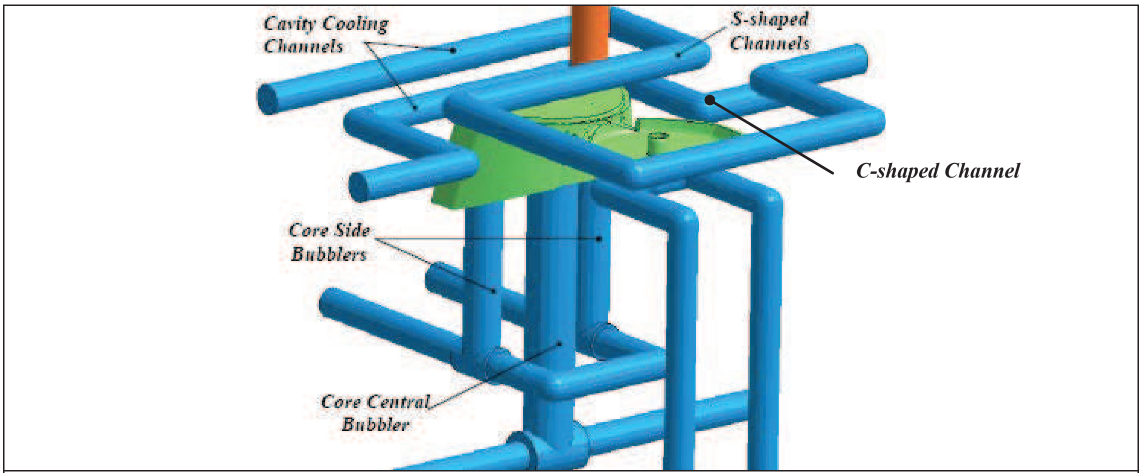
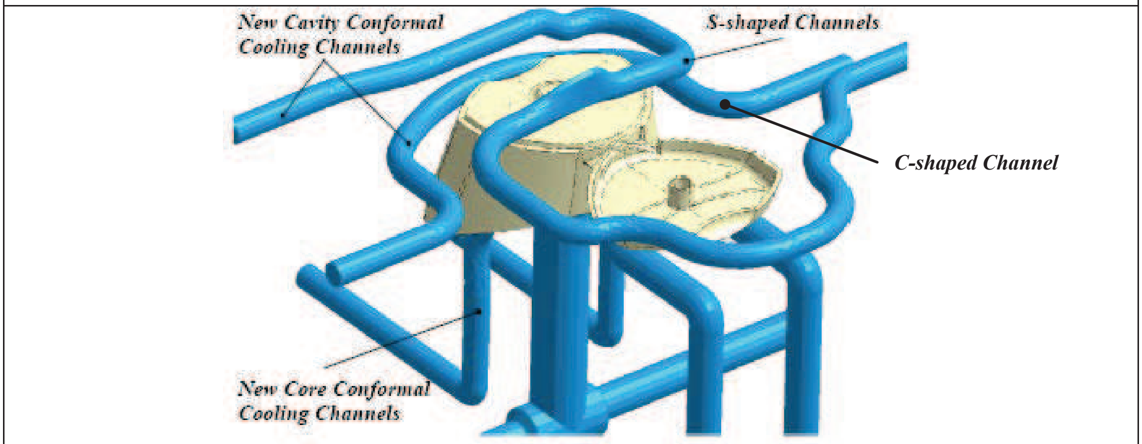
	
(a) Cavity	(c) Core

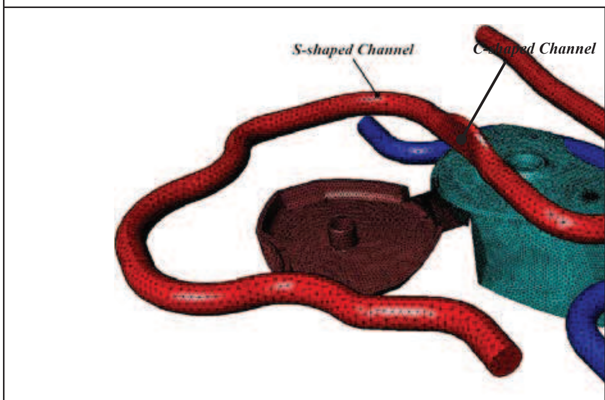
Figure 16 - Original CS3 Inserts



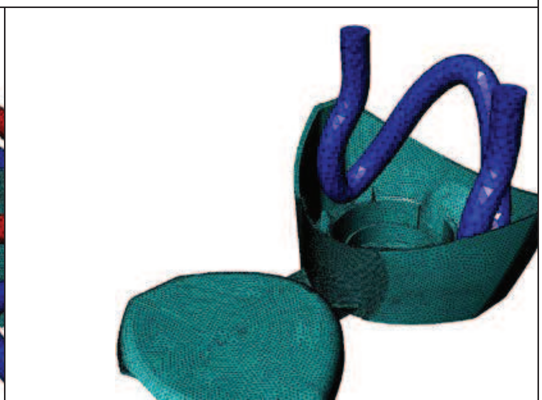
(a) Existing Cooling Systems



(b) New Cooling Systems

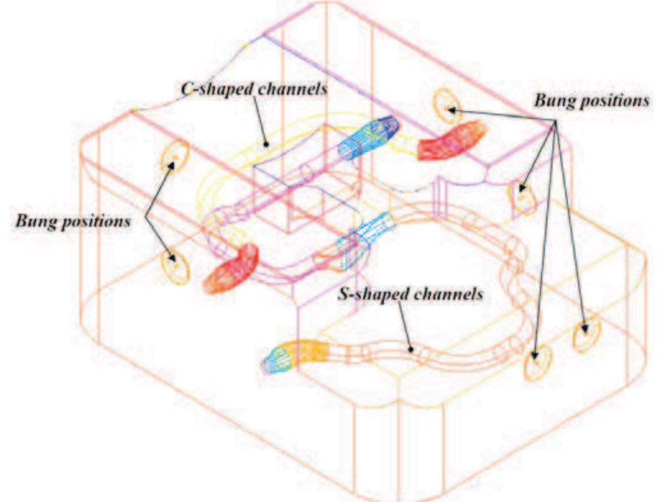


(c) New Cavity Conformal Cooling Channels

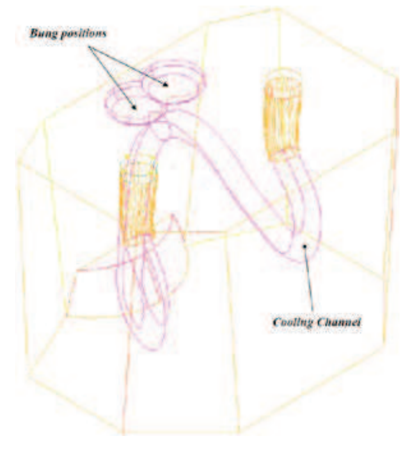


(d) New Core Conformal Cooling Channels

Figure17 - Existing and Redesigned CS3 Cooling Systems



(a) Cavity Insert



(b) Core Insert

Figure18. Wireframe of the Redesigned CS3 Near-Net Shape Inserts

(a) Cavity Insert

(b) Core Insert

Figure 19 - Green Parts of the New CS3 Inserts

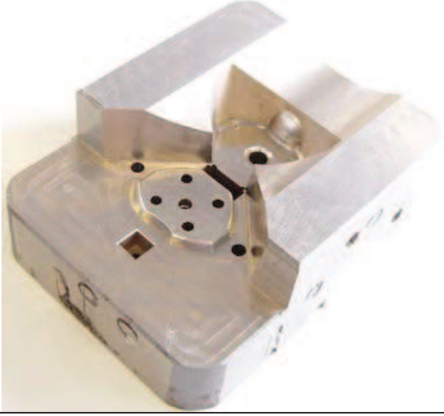
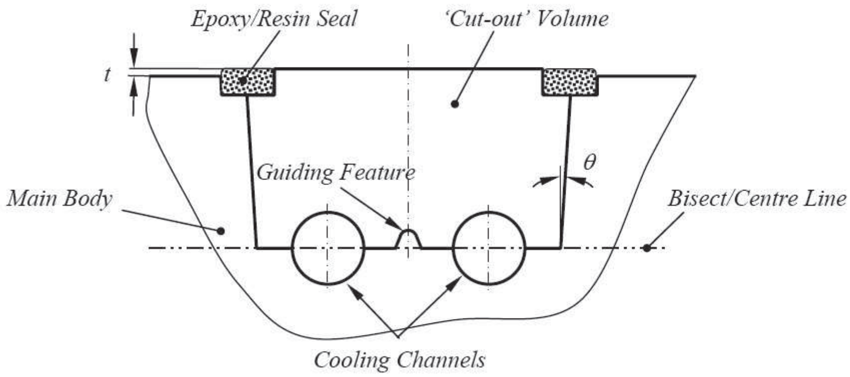
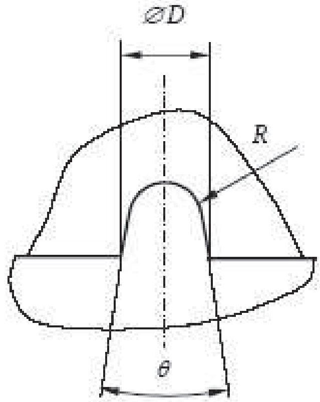
	
(a) Cavity Insert	(b) Core Insert

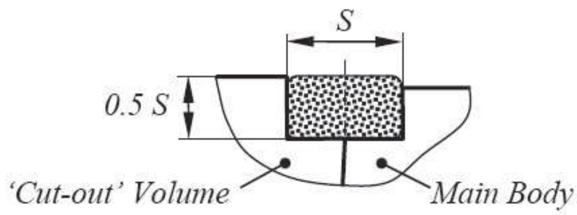
Figure 20 - Finished Redesigned CS3 Inserts



(a) Recommended Cut-Out Volume Features, with θ = 3-5º, t = 0.5-1 mm.



(b) Recommended Guiding Feature, with D = 5-10 mm, R = 0.5D, θ = 10º



(c) Groove Construction for Epoxy/Sealing Sealing, with S = 4-8 mm

Figure 21 – Cut Out Volume Recommendations