LARGE PARTS, SMALL SERIES: NEW MOULD ENGINEERING TECHNOLOGIES

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ABSTRACT

Low cost production of large polymeric parts in small quantities implies presently the use of non-conventional/artisan production processes like fibre reinforced resins (using open moulds) or rapid prototyping processes. Other solutions, specially the ones that require a closed mould and/or high pressures, are typically put aside due to the intrinsic costs of the required mould. As a direct consequence of this fact, the injection moulding process is not usually considered as an option, potentially constraining design issues like weight saving, aesthetic complexity, high dimensional precision and surface finishing. The aspects of poor geometric and aesthetic complexity may represent a major competitive disadvantage on the present market context and the ability to customize and differentiate a product, namely through design, is a decisive aspect for its market success. To overcome these difficulties new strategies are needed regarding the injection molding process. Using a case study part, this paper presents the work that has been carried on regarding the development and demonstration of new production processes involving non-conventional technologies/materials in the mould fabrication.

INTRODUCTION

Due to several factors, such as weight reduction, ergonomic and aesthetic improvement, increased product customization and multi-function incorporation within final parts and final products, there is currently a great demand towards the use of polymeric and composite [1] materials in large products manufactured in small series (less than a few thousands). The real constraint which limits the use of polymeric and composite materials in this sort of products is, essentially, the high cost of the mould. Since they are used for the production of small volumes of parts the high cost of the conventional moulds is translated in costly parts.

To cope with these necessities, current production processes resort to a multiplicity of technological solutions, from soft material moulds – epoxy resins (EP) [2], silicone, wood derivates, to several rapid prototyping based processes and to the injection moulds, using soft steels and aluminium alloys, manufactured by subtractive and additive technologies [3], [4].

Using the injection molding process as a starting exploration point, it was perform a comparative study of the application of different materials in cavities and cores for application in moulds destined to the production of small volumes (up to 500 units) of thermoplastic parts of large dimensions. The new tollbooth machine cover from BRISA, a Portuguese highway company, is used as a demonstrative part, but the concepts, technologies and know-how obtained, can be easily transposed to other applications and industrial sectors, from the large equipments to the aeronautics industry.

A sample part will allow a fast and more efficient knowledge generation through the development and evaluation of different manufacturing processes approaches. Within such context, multi-material cavities were produced in a "shell + substratum" conception and a set of tests aiming the evaluation of the basic criteria (part quality, cost and production time) and the respective use domain for such production tools. The result of this evaluation was systemized and presented in a matrix aiming the balance on the best options for application in the typified products within the scope of the case study.

THE CASE STUDY

Figure 1 presents the part that has been used along the case study.

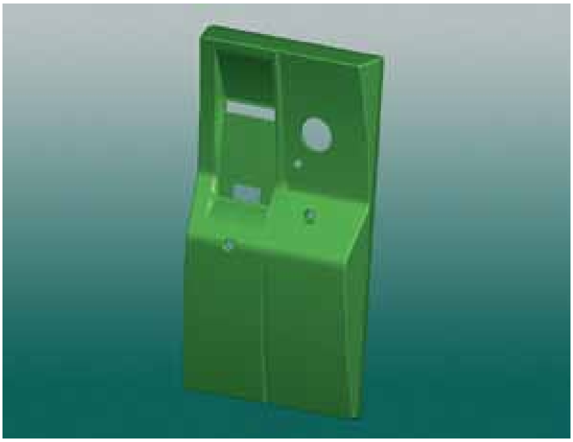

Fig. 1 – BRISA Tollbooth machine cover

From the client point of view the requirements for this part are the following:

- 50 parts up to 200 if market succeed
- Free forms, appealing image and ergonomics
- Impact and weather resistance
- Easy to assemble and disassemble
- Target Price – 200€ per part

To have a clear and detailed overview of the starting point regarding the technologic and economic solutions currently presented by injection mould makers, the part geometry and functional requirements were given to a qualified mould maker to design a mould and perform a comprehensive discrimination of the costs (Fig. 2).

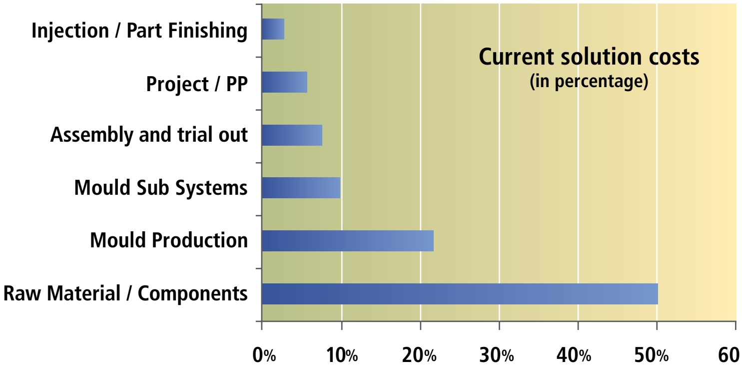

Fig. 2 – Part cost distribution

The mould was designed based on a conventional aluminium solution but not targeted to the objective, because the expected part cost was distant from the target cost. The economic analysis of the conventional injection mould was performed based on cost items and on a functional description of the mould. This analysis demonstrated where it would be most relevant to concentrate efforts, in order to minimize the tooling costs. The mould represents about 70% of the final part cost and more than 50% of the total cost of the tool is due to raw material of the structural components, followed by the machining cost and mould sub systems, such as ejectors, sleeves and guides.

During several brainstorming sessions potential improvement drivers were identified towards the objective of part cost reduction, and among others, there is the mould engineering driver, which will be developed along this paper. For this driver was recognized the following attack strategies, order by implementation priority:

1. Use of low cost and easy to machine materials;
2. Use of low cost technologies
3. Questioning the need of mould components and/or systematic simplification;
4. Reusability or share-ability of mould components;
5. Mould design reengineering based on a modular approach

An experimental methodology was devised to test the application of new mould materials and new technologies – first and second priorities.

EXPERIMENTAL METHODOLOGY

Considering the dimensions of the BRISA part (aprox. 800x400 mm) and the lack of knowledge regarding the technologies and materials under study, it was decided to test and evaluate them using a test part. A simple geometry was selected for this study (Fig. 3), with 300 mm of diameter and 60 mm of height.

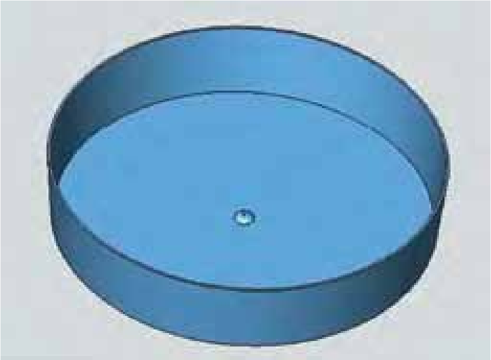

Fig. 3 – Test part

A simple mould (Fig. 4) was then designed contemplating besides the squared cavity and core, a typical injector and an air valve to facilitate the extraction of the thermoplastic parts. A frame was build with 4 steel plates fixed by screws and aligned to the back plate to help the alignment between the core and the cavities and to provide a support for easy assembly/removal of the cavities under study, among others. All together with the back plate, this mould frame has another important functionality. During the fabrication of the cavity it forms a supporting "box" assuring the best alignment for the building of the cavities.

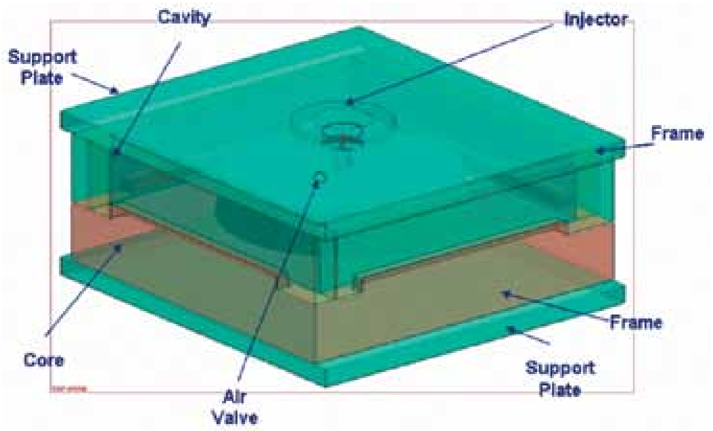

Fig. 4 – Mould design

The simplicity of the tool engineering was considered one of the fundamental criteria for the cost reduction. Each tool feature and component is only included if and only if it is strictly necessary to an adequate tool functioning and to the required quality of the moulded parts.

Three tryouts (TYO) were developed (Fig. 5). Each TYO consists in a mould following the above design, but fabricated with different materials and manufacturing processes. The first two were based on a moulding zone (cavity) that will be produced using a superficial "shell", strengthened by a second filling material. The last TYO was the conventional machined aluminium approach, normally followed by mould makers when dealing with moulds for small production volumes. The mould core was produced in aluminium by conventional machining technology. This approach allows a more cost efficient conclusions achievement as the core can be inter-changeable between the "standard" and the other 2 try-outs.

To produce the cavities in Spray Metal and in Resin EP it was necessary to build a master to generate the shape of the cavity for both processes. The master was built in polyurethane material, machined to final shape by turning and grinded afterwards. Then it was aligned and fixed with screws to the back plate of the mould, together with the mould frame. This assembly was used as the deposition box for the fabrication of both cavities.

	TYO 1	TYO 2	TYO 3
Shell	Spray Metal	Resin EP	Aluminium
Filling	Resin EP + Aluminium Powder	Resin EP + Aluminium Grains+Powder	Aluminium

Fig. 5 – Tryouts (TYO)

The operations sequences for the three TYOs are show bellow (Fig. 7).

MANUFACTURE PROCESSES

TYO 1: The cavity shell was produced using Spray Metal technology and it was reinforced through backfilling the shell with epoxy resin mixed with aluminium powder. The introduction of metal particles in the resins benefits the thermal and mechanical properties of the cavities. The process begins with the application of a demoulding agent over the polyurethane master and the base plate to facilitate the removal of the master from the metal shell at the end of the process. Afterwards a thin metallic layer was deposited over the master and the base plate through metal spraying (Fig. 6). Six layers of metal spraying were applied in sequence with a 15 minutes time span between each application. The objective was to obtain a final layer with approximately 1mm of thickness. Since this is a manual application process it leads to thickness variations difficult to control in advance.

Fig. 6 – Spray metal application

After the solidification of the metallic shell, the epoxy resin mixed with aluminium powder was deposited in the backside of the shell giving reinforcement to it. The mixture of the resin and the aluminium was done in a mixer equipment and was degasified in vacuum. The resin was then submitted to a process of cure in an oven during approximately one day. The cure of the resin was done using the frame and the mould back-plate as support box for filling. It was necessary to manually polish the cavity sidewall to improve the surface quality in order to facilitate the extraction of the plastic parts during the injection process. After been cleaned the cavity was ready to be used.

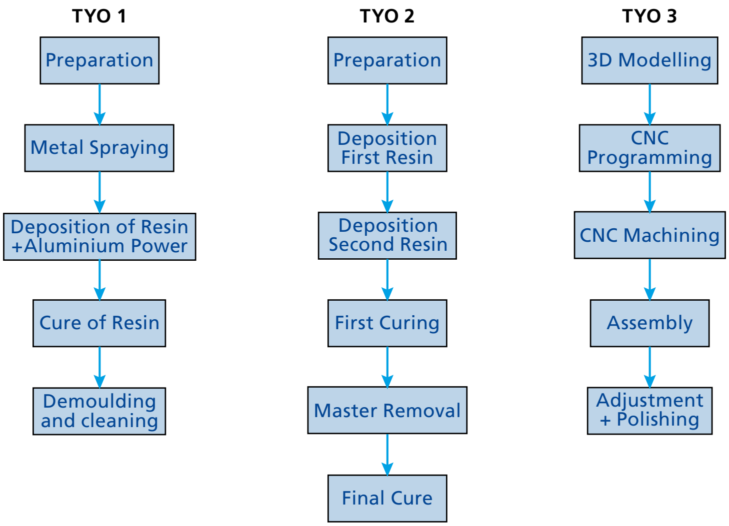

Fig. 7 – Operations sequence for moulds construction

TYO 2: This cavity shell was produced using a layer coating of non-filled epoxy resin, which was afterwards reinforced through backfilling with epoxy resin mixed with aluminium grains and powder. To begin the process of execution of the cavity in resin, the master was polished, painted, in order to eliminate irregularities and facilitate the demoulding process, and aligned with the mould frame and back-plate. After that a high temperature EP resin without any load was deposited over the master (Fig. 8). This resin will form a surface shell that will get in touch with the plastic material inside the mould. After the hardening of the first resin layer, the cavity was filled with the same resin but loaded with aluminium grains and aluminium powder. In the end of the deposition process, the resin inside the frame and back-plate was submitted to a 24-hour cure at room temperature and after that plus 4 hours at 60°C. Following the first cure the master was removed. Although there was demoulding agent used in the master the operation required some strength and care because there was adhesion between the two elements. After the master removing, the cavity was submitted to a new cure. Due to the lack of adhesion of the resin with the vertical walls of the master a very thin layer of resin was achieved in the sidewall (approximately 0,3 mm). Some small voids / sink marks were found in the sidewall of the cavity originated by this difficult adhesion of the first layer of deposited resin. The final surface quality was very good and there was no need for polishing.

Fig. 8 – Resin deposition on the master

TYO 3: The cavity was produced in aluminium through conventional machining technology. There were identified no major difficulties during the execution of this cavity. The polishing operation was needed for facilitating a good extraction of the plastic parts during the injection tests.

POST OPERATIONS

All cavities needed a drilling operation for the assembly of the injector. This operation would not be necessary in the TYO 1 and TYO 2 if an injector linked to the master was used before the deposition of the resin. Only the spray metal cavity was slightly polished in the sidewalls. Nevertheless all these materials can be submitted to post processing finishing operations with good results. Both components (core and cavity) where adjusted and tested assuring their functionality and the best working condition of the mould.

INJECTION PHASE

Three types of thermoplastic materials were considered for the injection tests: Polypropylene (PP), High Impact Polystyrene (HIPS) and Polycarbonate (PC). The first tests were carried on with the materials easier to process (PP and HIPS) through a production of 200 + 200 parts. After these injection series the condition of the cavity was analysed and depending on the results more 100 to 200 parts in PC were injected. The analysis of the quality of the injected parts was made on the basis of three evaluation criteria: dimensional stability, superficial finishing and injection defects.

RESULTS EVALUATION

The analysis of the test cavities was made based on the following evaluation criteria:

Materials Cost: For each cavity the materials and components costs were quantified based on the necessary quantities to produce the cavity (Fig. 9).

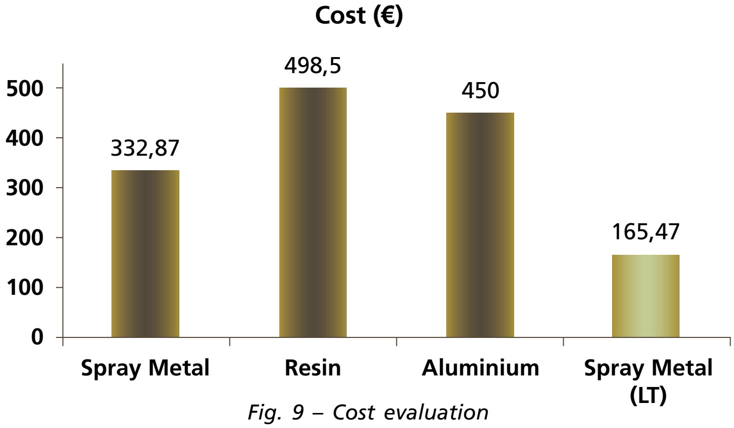

Fig. 9 – Cost evaluation

As a starting point and in terms of material costs both solutions are economically competitive with the conventional aluminium cavity. In fact the spray metal cavity (including the master material) is approximately 10% less expensive than the aluminium one. The cost of material used in the shell is not very representative because of the low thickness used. Since the shell is the contact surface where the demands are tougher during the injection moulding, resins compositions that support the high temperatures, the wear and the pressures that take place in this zone should be used. There is no need for such properties in the backfilling material that represents the major volume and cost. For the two cavities using resin for backfilling (TYO 1 and 2) it was used high temperature resins loaded with aluminium material.

These resins are much more expensive than the low temperature (LT) ones. If in the injection tests the results achieved are good as the analysis of the cavities allows to foreseen, one can expect that it is possible to use LT resins and subsequently lower the mould cost. Taking as example one cavity with a shell in spray metal and a back-filling of a LT resin, a cavity at a cost of 165 € (last column on Fig. 9) is expectable.

Production Time: For all cavities, the operations times involving labour and equipments were registered during the different production phases (Fig. 10).

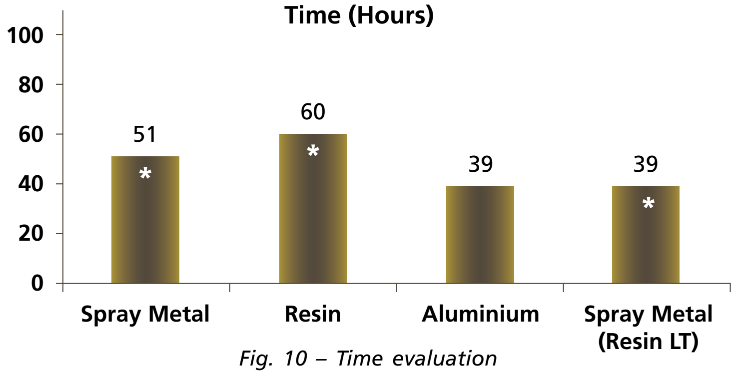

Fig. 10 – Time evaluation

The processes involved in the execution of the cavities 1 and 2 are very dependent of human labour and that, added to the time required to the resin cure, result in large time consuming processes when compared with TYO 3. Yet, it should be remarked that the times presented are the real ones spent in the research process. So it is expectable a large reduction on the consumed time on the fabrication of cavities 1 and 2 based not only on the process industrialization but also on experience, learning and best practices definition. The last column (Fig. 10) is a potential time for the solution of Spray Metal with LT resin backfilling.

Accuracy: The produced cavities where analysed relatively to geometric alterations and dimensional deviations (height, diameter and form). When the injection moulding tests were performed, the cavities were analysed again at the end of production to compare their degradation under operation.

Finishing: The analysis of the surface finishing of the cavities was made by visual analysis and through measurement of the surface roughness. This analysis was done also after the injection tests to evaluate eventual alterations in the surface influenced by the injection process.

Recycling and re-utilization: The shells in the cavities should be done with new material to maintain the best control over the properties at the moulding and parting surfaces, but theoretically the materials used previously for the fabrication of cavities 1 and 2 can be 100% reused as backfilling material to produce new cavities. This implies an operation of breaking the used cavity materials to small grains. The behaviour of such reused materials in new moulds will be studied and evaluated in future tests. The impact over the mould materials cost depends on the percentage of reused materials, but a significant reduction on the filled material can be expected.

The results of the analysed cavities are presented in the following evaluation matrix (Fig. 11) quantified in a scale of five values, being 1 the value of less performance and 5 the value of best performance. This quantification is resultant from quantified data for each one of the previous evaluation items that were analysed separately.

		Classification				
		1	**2**	**3**	**4**	**5**
Material Cost				**T2**	**T3**	**T1**
Time			**T2**		**T1**	**T3**
Accuracy	**Diameter Deviation**			**T1** **T2**		**T3**
	Depth			**T2**	**T1**	**T3**
	Concentricity			**T2**	**T1**	**T3**
Finishing	**Roughness**			**T1**	**T3**	**T2**
	Visual Aspect			**T1**	**T2**	**T3**
Resistance					**T1** **T2**	**T3**
Recycling Reutilization			**T3**		**T1** **T2**	

Fig. 11 – Evaluation Matrix of the Results
(T1=TYO1; T2=TYO2; T3= TYO3)

A simple analysis of the matrix above allows representing a comparison of the three TYOs. Attributing the same weight to the five different evaluation criteria and considering the TYO 3 as the standard case, case 1 and case 2 are very close to the standard, allowing to foreseen the success of new developments and further research (Fig. 12).

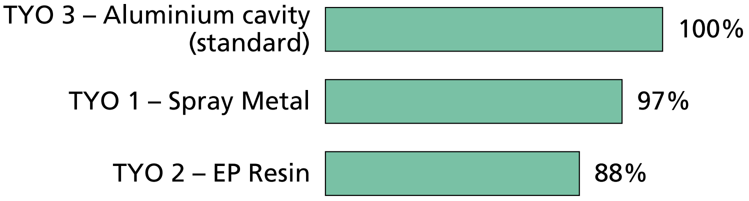

Fig. 12 – Tryouts comparison put side by side

Additional Materials Research

With intention of reducing costs in materials for reinforcement of the shells in future cavities, several tests of mixtures of resins with different loads (mixing material) where performed with the objective of determining one composition that could be used as backfilling with the lowest possible production cost. Obliviously the higher potential cost reduction using the approach of "shell + substratum" lies in the later where higher material volumes and less demanding properties are required. Five different compositions were designed with the goal of producing future new cavities (Fig. 13):

- Resin with sand (large grain), with a weight proportion of 1:6
- Resin with aluminium chips – 1:1
- Resin with sand (large grain) – 1:9
- Resin with sand (large grain) and aluminium chips – 1:3:1
- Resin with sand (thin grain) – 1:7

The mixtures were casted in small equal boxes and were submitted to a process of cure. As a common base material for all cases it was used a low temperature resin.

Fig. 13 – Test samples

All sample mixtures shown good behaviour during curing process and come out as potential for application as material for reinforcement of the shell cavities. The samples using sand material present the best homogeneity, but the thermal and mechanical behaviour should be tested in working conditions. It's also important to evaluate the behaviour to machining operations, like drilling. The samples using aluminium chips have a worse homogeneity when compared with the ones with sand but this is due also to the dimension and shape of the grains. Nevertheless for the application in analysis these mixtures can also be used with the advantage of better thermal properties and easier to machine proprieties.

CONCLUSIONS

The work done until now demonstrated innovative tooling approaches based on "shell + substratum" principles which are not common in mould making industry. In fact, if the technologies are not new by themselves (applications are reported mainly in the prototype field and for small parts) the way they are used and explored in a small production volumes and large parts context are clearly innovative and lead to a set of problems that required tailored solutions case by case. The preliminary analysis of the produced moulds gives a very positive expectation relatively to the part injection trials.

This research will continue with new injection tests using the Spray Metal solution and new low cost backfilling materials. The use of backfilling recycle materials from the already produced one is also foreseen. One of the next steps is also the construction of "features" normally encounter in production plastic parts, like ribs, snap fits, on the sample part design, and evaluate the behaviour of the new mould materials with these technical challenges. An exhaustive analysis will be making along all the process to generate knowledge as regards the cavities behaviour on injection conditions and to derive best engineering practices.

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