SYSTEMATIC TO OVERCOME CNC MACHINING LIMITATIONS IN RAPID TOOLING

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Abstract. *The use of CNC machining as a Rapid Tooling (RT) option to obtain prototype tooling using polymeric resins (epoxy or polyurethane based), has some advantages when compared to Rapid Prototyping (RP) technologies. Among them, good dimensional accuracy and surface roughness. However, some limitations are related mainly to geometries that can not be easely milled, such as corners, undercuts and others. Usually, Electrical Dischard Machining (EDM) is extensively used in the tooling sector to manufacture metalic material. However, it can not be used with polymeric resins. To deal with CNC machining problems, the main milling limitations were investigated for RT and then a systematic to overcome them was proposed. The idea is to divide the insert geometry in small parts easier to machine (small inserts), machine them separately and finally, assemble all the small parts into the core and cavity afterwards. The same idea can be used in regions which require slides (undercut parts). To test this systematic, this work presents two case studies where these problems were addressed. After the machining and assembly, it was possible to inject one hundred prototypes in polypropylene using an industrial injection moulding machine. The results show that it is possible to apply the proposed systematic in prototype tooling application with polymeric resins.*

Keywords*: Rapid Tooling, Milling, Small Inserts, Polymeric Resins*

1. INTRODUCTION

In the product development process of a plastic injected part, a functional prototype may be obtained using prototype tooling (also known as prototype mould). The core and cavity inserts for this kind of tool can be produced either via Rapid Prototyping (RP) techniques or using CNC (Computer Numeric Control) machining (Ahrens *et al.*, 2002). The term Rapid Tooling (RT) was introduced after the advent of RP process, but today other processes besides RP can be included in this context. An example is CNC machining, either conventional or High Speed Machining.

The CNC machining aided by CAD/CAM (Computer Aided Design/Manufacturing) systems is a good option to manufacture these prototype moulds. The main advantages of this technology are related to a high dimensional accuracy, good surface finishing and the variety of material that can be used. Some easy to machine materials, such as polymeric resins (epoxy or polyurethane based), have been developed for injection mould application, speeding up mould manufacturing (Lanz *et al.*, 2002, Yang and Ryu, 2001). A good result with one of these materials was reported by Yang and Ryu (2001), applying to inserts with geometries that can be easily reached by a cutter (mill, drill, etc.). Volpato *et al*. (2003) also reported good results using epoxy resin for a prototype mould. However, when a mould has undercut regions, which require slides, or deep slots to form ribs and bosses, milling machining might not be enough to obtain these features. These kinds of features do not prevent a prototype mould from being built and used though. One example of this is a process called Protoform, where usually aluminium is used in a rather puzzle-like prototype mould (Protoform, 2005). In this process all the undercut regions are designed to be manually operated (assembled and reassembled after injection). In this case, CNC machining is used combined with Electrical Discharge Machining (EDM) to obtain the features that can not be attained via milling.

In a similar way, in the manufacture of a production mould, different processes are combined to obtain all the geometry details (Rosato *et al.*, 2000). EDM plays a very important role in this area, but it is a rather slow process. Notwithstanding, when one intends to obtain a prototype mould as quick as possible and, therefore, chooses only easy to machine polymeric resins, the EDM process can not be applied, because of the non-conductive nature of this material.

One way to avoid EDM and to use only milling to obtain all details in the core and cavity inserts is to divide the problematic regions in easier to machine geometries and extract them from the main inserts. The extracted parts generated are called here small inserts, in order to differentiate them from the core and cavity inserts. The small inserts are then machined separately in the same resin and assembled in the main inserts later. In this case, the inserts and the small inserts can be obtained only by milling in a 3-axis CNC machining centre. In order to help the prototype mould manufacturer to use this idea, this work presents a systematic containing the main steps and some suggestions to produce the small inserts. Although it seems a simple proposal, the implementation is rather tricky; therefore it is useful to set some general guidelines and also to suggest practical solutions to simplify small inserts manufacturing.

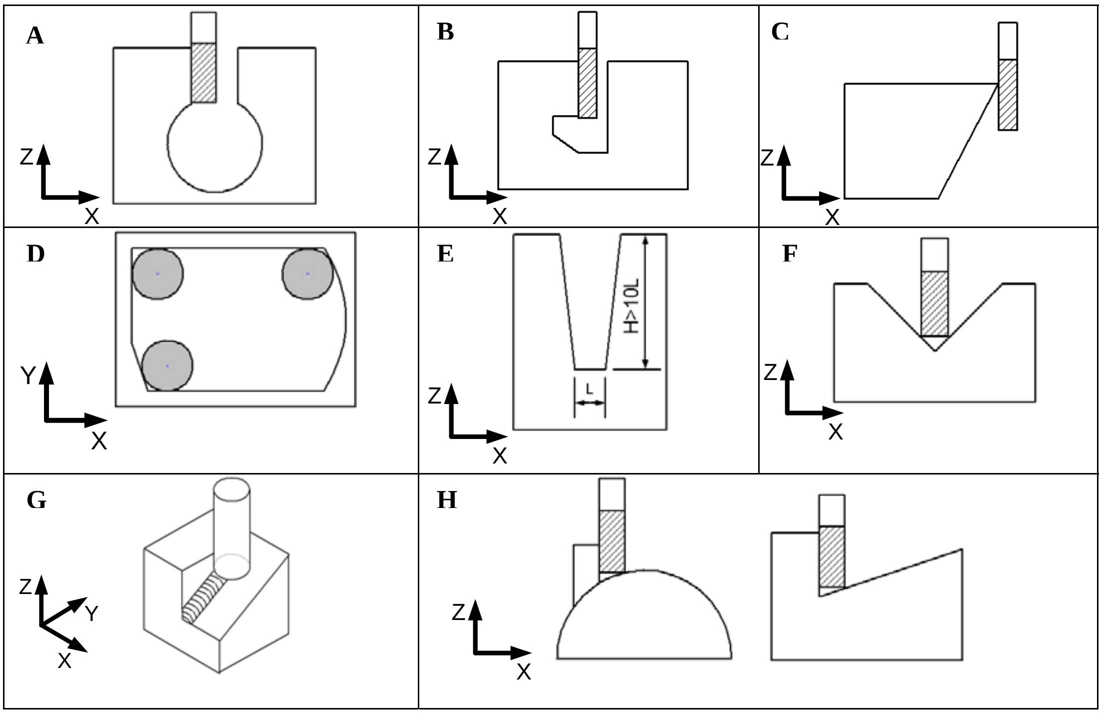
In this work, firstly a discussion about the main milling geometric limitations to obtain injection mould inserts is presented. Then, the proposed systematic is described with each step being explained in details. To test the idea, two case studies were carried out where plastic parts which require the use of small inserts were chosen. The systematic was applied and the inserts for the two parts were manufactured and assembled. After machining it was possible to inject one hundred prototypes in each mould using an industrial injection molding machine. The discussion and conclusion presents pros and cons about this idea.

2. GEOMETRIES DIFFICULT TO OBTAIN IN RT WITH CNC MILLING

The development of CNC and CAD/CAM technologies represented a great breakthrough in design and manufacturing of complex geometries typically found in injection moulds. In spite of this, it is well known that some geometry details can not be obtained only by milling. Radstock (1999) mentioned that the main limitations are related to obtain undercuts and straight corners. In another work, Volpato and Amorim (2004) reported that a slot in which height is 10 times greater than width poses difficulties due to limitations in cutter length.

In order to illustrate these limitations, Table 1 presents schematically a compilation of geometries which are considered problematic to obtain by milling. The letters A, B and C represent undercuts and regions that can not be reached by the cutter (mill). Letter D represents straight corners in the XY plane and letter E refers to deep slots (usually to form ribs in parts). The letters F, G, and H show situations where material is left underneath the cutter. It can be observed that even if a 5-axis machine is available, only the cases represented by letter C, F and G, dependent on the surface angle, may not be considered a problem for milling machining.

Tabela 1. Examples of geometries difficult to be machined by milling



H = Height, W = Width

3. METHODOLOGY

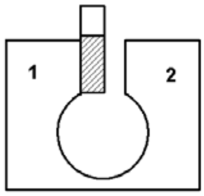
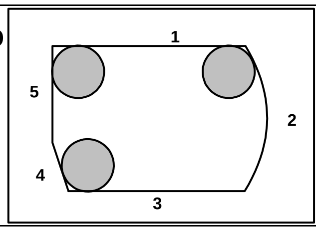
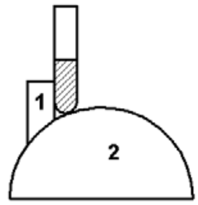
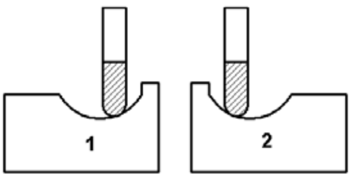
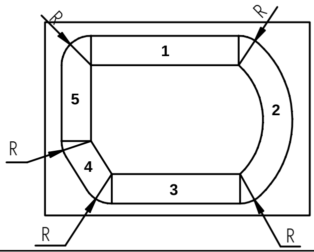
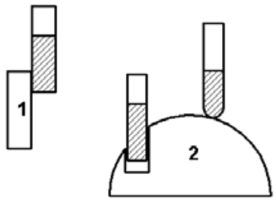
The difficulties presented above are easily found in core and cavity inserts. To overcome these problems, the idea is to simplify the regions by divide them. In order to create a systematic approach to design and manufacture the inserts, a procedure was developed in the Prototyping and Tooling Group (NUFER) at UTFPR. The Design For Manufacturing (DFM) principle needs to be applied in this process in order to have good results. This is because there is an overlapping between the design and manufacturing activities in the injection mould area. The proposed systematic can be divided in nine steps. The following paragraphs explain each of these steps.

Step 1 – Identify problematic regions: In this first step, all the regions that offer difficulties to be machined by milling have to be identified. Table 1 can be used to help in this task.

Step 2 – Design and extract small inserts: Once problematic regions have been identified, the geometries of the small inserts should be defined (designed) and extracted from the main core and cavity inserts. In this process, a CAD file for each small insert is created. It is important to design them avoiding causing any change to the main insert geometry, by altering it. The cut direction to extract the small inserts and the direction of the mould extraction are the same, then, one should be careful with the draft angle of the features. By choosing the bottom lines or contours of the draft surfaces to create the cut, the geometry of the insert can be preserved. Another important point to be observed is that the small insert needs to have rounded corners in the XY plane. This is because the insert bed formed in the main inserts has to be milled (see restriction D in Table 1). DFM is well suited in this task because the shape and locations of the small inserts have to take into account the limitations of the machining process. An important observation in this step is the use o common sense to avoid define small insert too small, which will be difficult to handle in the manufacturing process. In addition, some small milling problems could be discarded and left as they are based on the prototype functionality analysis.

In order to clarify the procedure in this step, Table 2 presents some examples of small inserts that might be designed based on the regions identified in Table 1. For undercut details, such as clips, etc., the geometry of the small inserts should simulate a slide, which, during the injection process, will be extracted together with the moulding from the main insert. The small insert needs to be removed manually and reassembled in the insert for the next injection cycle (Figure 1). These kinds of inserts were defined as removable small inserts, to differentiate them from those that have to be fixed, defined as fixed small inserts. Here there is a point that has not been addressed in the literature, i.e. the use of this kind of slide solution for prototype tooling using polymeric resins. One of the open issues is whether it will be necessary to use extractor pins to push the small removable insert or if the molding would be able to pull it form the beds. All tests reported in the literature used rather simple test part geometry. The proposed solution is tested later in this work.

Table 2. Example of some small inserts possibility

Problematic Regions	**A** 	**D** 	**H** 
Examples of small inserts			

Another detail to be observed is the height of the small inserts. The height of the insert is generated by the depth of the cut to extract it (or the depth of the bed) and should be enough to accommodate two sections. The first one is the guide region (upper region), which is obtained accurately by CNC machining and is responsible to locate the small insert in the XY direction in the bed. The other is the bottom rough region, which will be obtained manually in a post-processing stage, and is thought to facilitate the clamping in the machining. This latter section will be the bottom of the small insert as it is located in the base used to clamp the blank in a vice. In order to simplify the manufacturing process, the small inserts can be machined altogether in one blank (Figure 2 – see step 4). Only the accurate section of the small insert needs to guide it into the insert bed and the base can be roughly and quickly finished to a smaller size.

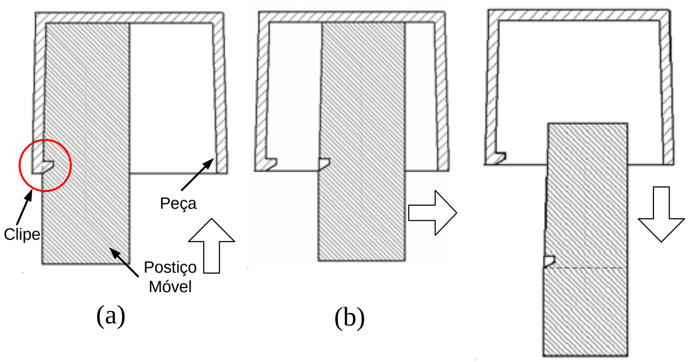


Figure 1. Removable small insert steps

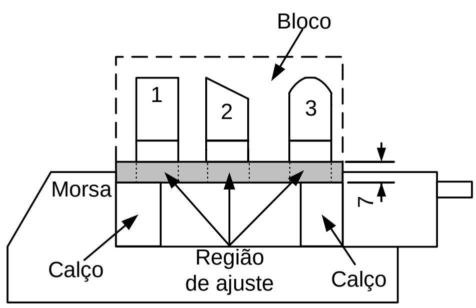


Figure 2. Small inserts assembly for machining

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Step 3 – Create the small inserts bed: If the generation of the small insert beds in the main core and cavity inserts does not involve undercuts, it can be easily done by boolean operations. The CAD model of the small insert obtained in the previous step is inserted into the main insert model and subtracted from it. As the position and orientation of the small insert in relation to the insert origin (CAD origin) are preserved during the extraction stage, the boolean operation is quite straightforward. It is expected that in following this procedure, the fit between the two mating parts (guide and bed) will be of the interference type (negative clearance) after machining. Therefore, some manual work will be necessary.

Step 4 – Assemble the small inserts in a blank: As mentioned before, all small inserts, if possible, should be assembled in one blank, with a distance between them which allows a cutting tool to contour each one. In addition, the bottom face of the small insert must match the bottom face of the blank. This assures that the small insert height is easily obtained during machining, guarantying the position in the Z direction. This procedure facilitates clamping the small inserts in the machining process and handling in the CAM system. A vice can be used to fix the blank and therefore the tool is free to move around all details.

Step 5 – Generate the CNC machining strategies: All CNC machining strategies are generated using a CAM system. No special requirement is necessary in this step, apart from a 3D machining module.

Step 6 – CNC machining: The CNC machining can be carried out in a 3-axis machining centre. No special requirement is necessary in this step. However, if a 5-axis machine is available, the number of small inserts can be reduced.

Step 7 – Cut and adjust the small inserts: After CNC machining, the small inserts should be separated from the blank base using a saw (automatic or manual) and the small insert base should be roughly adjusted to remove the excess material. Electrical tools can be used to speed up this operation. It is important to remember that the bottom surfaces of the small inserts do not have to be finished; they should remain as the original blank surface.

Step 8 – Assembly of the small inserts in the main inserts: The final task before injection is to assemble all the small inserts in their respective beds in the core and cavity inserts. Some few manual adjustments may be necessary in this operation.

Step 9 – Injection process: The injection process using a prototype mould should be carried out carefully. The insert strength is not very high and therefore the injection parameters should be set accordingly. In the machine setup, the number of shots before the first good part is obtained should be kept as low as possible, to preserve the inserts from an early damage. If any small insert is simulating a slide, the machine operator should be prepared to remove and manually reposition it into its bed.

4 CASE STUDY

4.1. Case Study 1

This first case study was designed to check the proposal and also to analyze how the two kinds of small insert (fixed and removable) will behave during injection. Figure 3 shows the test part geometry designed for this purpose. The part material chose was Polypropylene (PP), the wall thickness was 2mm and a draft angle 1.5º. A clip was included on the part lateral in order to use a removable insert. Another feature designed was the central rib (2x28mm) requiring a deep slot in the core insert, which is not possible to be machined directly as the height and width relation is higher than the usual milling tool diameter and length relation (H=10W). Finally, the straight corners in the cavity side also require fixed small inserts to be generated.

4.1.1 Inserts definition (Steps 1-3)

The CAD system SolidEdge V18 was used to obtain the part model and also the core and cavity inserts. Using Table 1, the regions which can not be machined were identified (Figure 4a and b). The injection point was defined on the part lateral (opposite to the clip) and the gate geometry was based on the good results obtained in a previous study (Volpato *et al*., 2003).

Once the problematic regions have been identified, all the small inserts geometries were designed to allow milling. The suggestions from Table 2 were used to design them. Figure 5 (a) and (b) present all small insert necessary for the test part 1. With the CAD model of the small insert, their respective beds were generated using the boolean operation (step 3).

4.1.2 Inserts manufacturing (Step 4-8)

Following the 4th step, all the small insets were grouped in one blank (Figure 6). To allow tool access to machine the clip head in the removable small insert 1 (Figure 5a), it was positioned close to a corner of the blank. Because of it, the blank need to be rotated and fixed in a new position in the CNC machine. All the machining strategies were created using the CAM systems PowerMill 5.5. The material used in the insert was Ren Shape 5166 from Huntsman, following the study of Volpato *et al*. (2003).

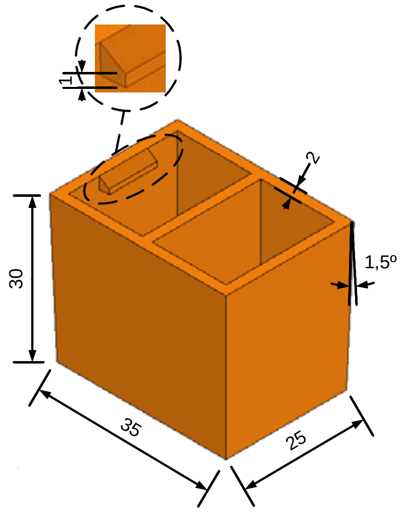


Figure 3. Geometry of the test part 1

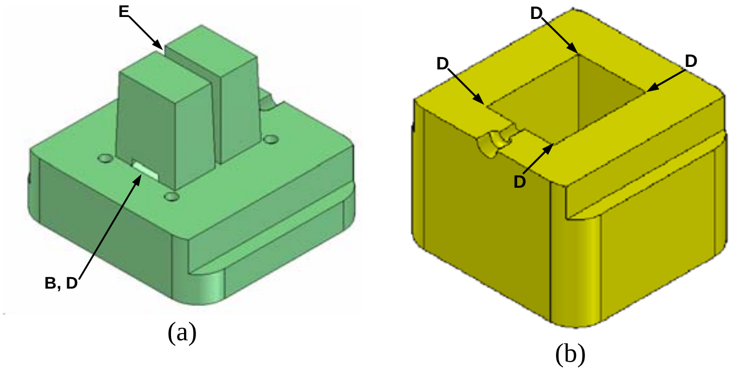


Figure 4. Core (a) and cavity (b) inserts for test part 1

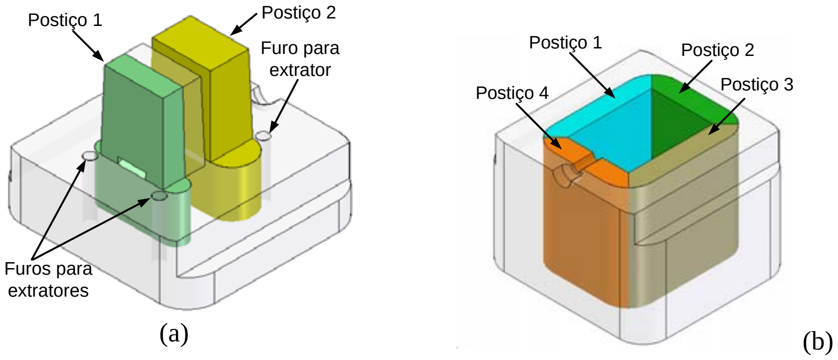


Figure 5. Small inserts created for the core (a) and cavity (b)

After machining, the small inserts were separated from the base. The base regions were manually adjusted with the aid of an electrical tool as can be seen in Figure 7. Fine sand paper (grit 600) was used in the guide region of the inserts to fit them to their respective beds. For the fixed small inserts an interference fit was sought. Then, the allowance between the small inserts and the bed were set to 0,02mm (small insert dimension smaller than the bed dimension). For the removable small inserts, a clearance fit was sought, allowing sliding between the mating parts, i.e. allowing the small inserts to be extracted together with the molding, without the need to use an extractor pin to push them. In this case, the allowance was 0,05mm, also with the small inserts smaller than their beds. These values were defined empirically, via trial end error until they seems appropriated to each case. Only the final test in the injection process would prove their success or failure. Figure 8 shows the core and cavity inserts already assembled and ready for the injection.

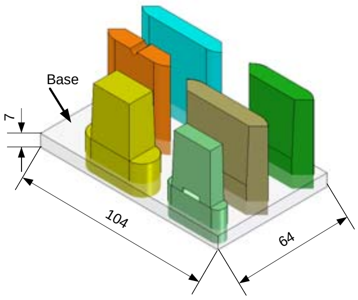


Figure 6. Blank with the small inserts

Figure 7. Small insert manual adjustment

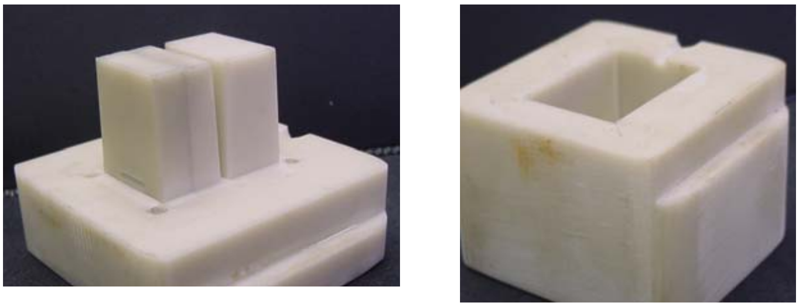


Figure 8. Main inserts with the small inserts assembled and ready for injection

4.1.3 Injection process of the prototypes (Step 9)

The inserts were assembled in a standard injection mould designed to this purpose. The injection process parameters (injection temperature, speed, pressure, holding pressure and holding pressure time) were defined following the short shot method proposed by Barry *et al.* (1995). Table 3 presents the injection process parameters for test part 1, which required 22 shots to be defined. Compressed air was used to cool down the insert and a new shot was only started once the temperature of the inserts reached 42 ºC, following Volpato *et al.* (2003), which used the same pair of insert and molding material. The temperature control was done with an infrared thermometer (Minipa MT-350), measuring the insert surface on different positions. This procedure is important in order to extend the life of the inserts.

One hundred (100) parts were injected. This number was the limit found in a study carried out in some companies which work with product development (Amorim *et al.*, 2006).

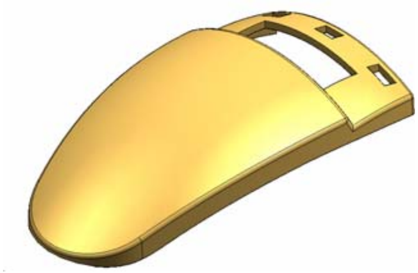
Table 3. Injection process parameters for test part 1

Parameters	**Value**
Temperature (ºC)	180
Speed (m/s)	60
Pressure (bar)	100
Holding pressure (bar)	50
Holding pressure time (s)	3

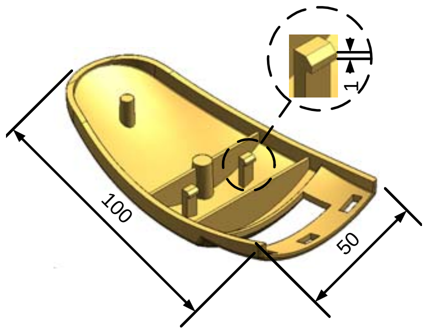
4.2 Case Study 2

In this study, the procedure was applied to a mouse top case part, which is more complex than the geometry of case study 1 (Figure 9a and b). The idea was to test, in a real part, the systematic to generate and manufacture the small inserts and also to test their performance. Figure 9b shows in details two clips, which requires the use of removable inserts. In the part central region there are two ribs with the critical dimension of 1x12mm. The height and width relation is higher than the usual diameter and tool length relation available (Table 1).

Once the inserts were extracted in the CAD system, it was observed that all regions in the cavity insert were possible to be milled. On the other hand, many problematic regions were identified in the core insert following the types presented in Table 1. Table 4 presents a summary of the main steps of the procedure as they were similar to the steps carried out in the case study 1. Table 4-step 1 shows all the problematic regions of the core insert. The main problem was the two clips (type B problem), which required removable inserts (small inserts 5 and 6 in Table 4-step 2). Problems related to material left underneath the cutter (types G and H problem) were found in the splitting surface and around the small features in the front of the insert. It was observed that these regions in the final molding do not play a relevant roll in the part function. In addition, using a small diameter cutter, the amount of material not removed will be very small, not causing considerably influence on the final geometry. Therefore, it was decided not to create vary small inserts to solve these problems. To machine these regions in the main inserts and also in the small inserts 1, 2 and 3, an end mill of 1mm diameter was used.



(a)

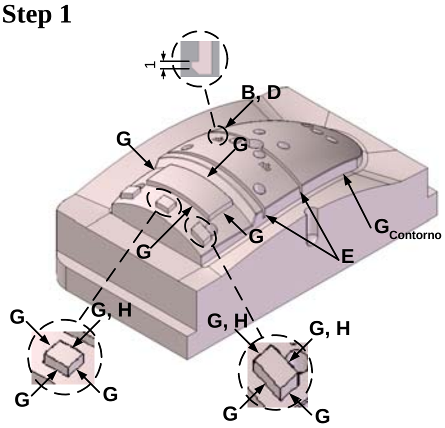
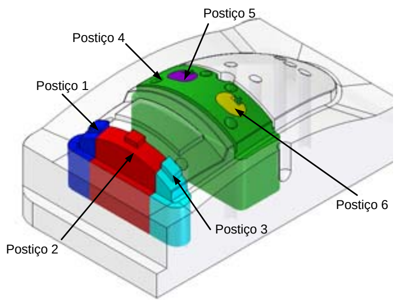
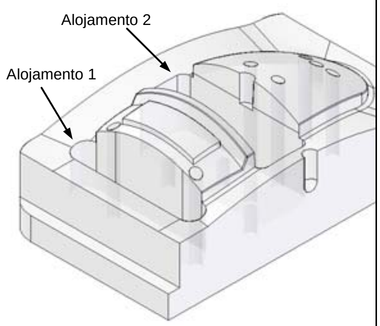
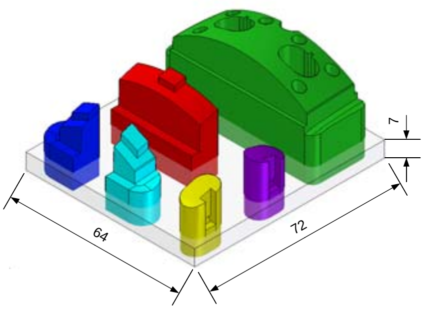


(b)

Figure 9. Mouse case geometry - part 2. External side (a) and internal side (b)

Based on the identification of the problematic regions, the small inserts were designed, extracted and the respective beds generated as can be seen in Table 4-step 2 and 3. In Table 4-steps 4-6, all small inserts were grouped in one block to facilitate manufacturing, similar to what was defined in the case study 1. Table 4-step 7-8 shows the two inserts ready to be assembled in the injection mould.

Table 4. Summary of the main steps of the case study 2

Step 1	**Step 2**	**Step 3**
		
Step 4-6	**Step 7-8**	
	 	

The same fit procedure and allowance used in test part 1 were applied in the small inserts, i.e., 0,02mm for the fixed small inserts and 0,05mm for the removable ones.

Table 5 presents the injection process parameters for test part 2, which required 16 shots to be defined, and were used to inject 100 prototypes. The same procedure to set up the injection machine and to control the injection process used in the case study 1 was applied.

Table 5. Injection process parameters for test part 2

Parameters	**Value**
Temperature (ºC)	180
Speed (m/s)	120
Pressure (bar)	140
Holding pressure (bar)	70
Holding pressure time (s)	6

5 RESULTS AND DISCUSSIONS

5.1 Case Study 1

The number and shape of the small inserts in this case study allowed the reproduction of all problematic regions identified. The shape solution proposed for the clip removable small insert resulted in some rounded corner left by the milling radius (type D problem) at the clip head. These rounded corners were considered not relevant to the part functionality and the small insert designed was considered satisfactory.

The idea to group the small inserts in one block to be machined facilitated the tool path strategies generation and the CNC manufacturing process. As it was expected in the procedure, the small inserts needed some manual post processing in order to be assembled in the main inserts. After the manual sanding of the small inserts, it was verified some gaps that exceeded the intended allowance values of 0,02mm and 0,05mm for the fixed and removable small inserts respectively. An even material sanding proved not to be easy, and some excess were observed. Figure 10 shows some gaps in the cavity insert.

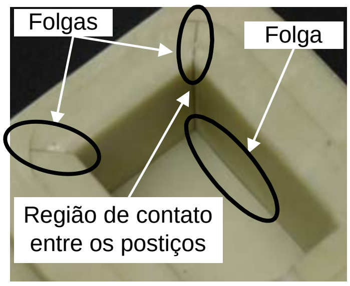


Figure 10. Gaps observed in the cavity insert of the test part 1 after assembly

In all 100 parts injected, the removable small inserts worked fine, being extracted with the molding and reassembled in the main insert (Figure 11). This test showed that they can be extracted by the molding, not requiring extractor pins. The fixed small inserts also worked as expected, i.e., did not move during injection. Due to the gaps reported before in the cavity insert, some flashes were observed outside all injected parts (Figure 12a). Another problem found was an inclination in the internal rib wall (Figure 12b). Probably, this is due to the deformation of this region as the flow of the melted plastic enters the cavity. The injection pressure applied on the wall beside the removable small insert must have deformed it. The injection flow could be better balanced by repositioning the gate on the part lateral. A better structural analysis of this problem should be carried out to identify the possible causes.

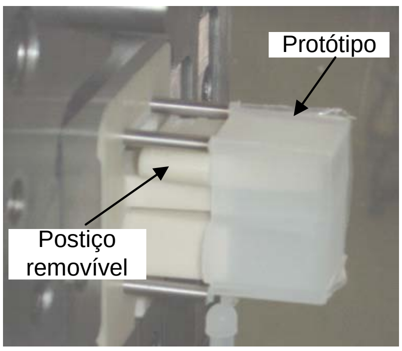
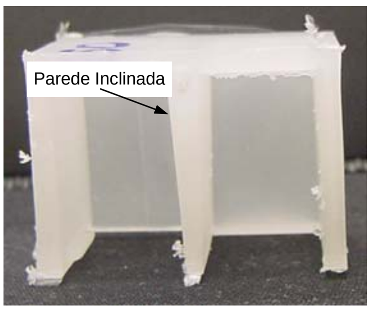


Figure 11. Removable small insert during extraction of the molding

(a)



(b)

Figure 12. Flashes (a) and inclined wall of the rib (b)

5.2 Case Study 2

Similar to the case study 1, the solution proposed for the removable small insert for the clip resulted in some rounded corner left by the tool (type D problem). These rounded corners were also considered not relevant to the part functionality and the small insert design was considered satisfactory for the final molding. The material left underneath the tool (type G and H problems), which were not addressed in the inserts, were really vary small. As can be seen in Figure 13, it is not possible (with the zoom used in the picture) to identify the material left, showing that the 1mm tool working with the CAM corner finishing strategies did a good job. It is also possible to say that, if these types of problem is in a relevant regions of the prototype, it can be solved by a manual post processing, as the material is relatively easy to machine.

As observed in the test part 1, after assembling the small inserts, some gaps were observed, mainly between the removable small inserts and their beds (Figure 14). These gaps were caused by excessive sanding in some points.

Figure 13. Material left by the 1mm diameter tool

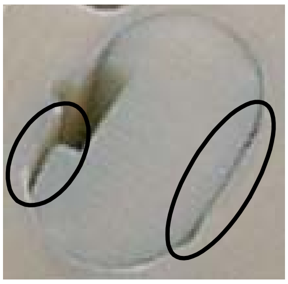


Figure 14. Gaps in the removable small insert

Figure 15 shows one injected prototype of the test 2. Again in all injections the removable inserts were extracted by the molding without the need of extractor pins. Due to the gaps mentioned before, some flashes can be observed in the clip regions.

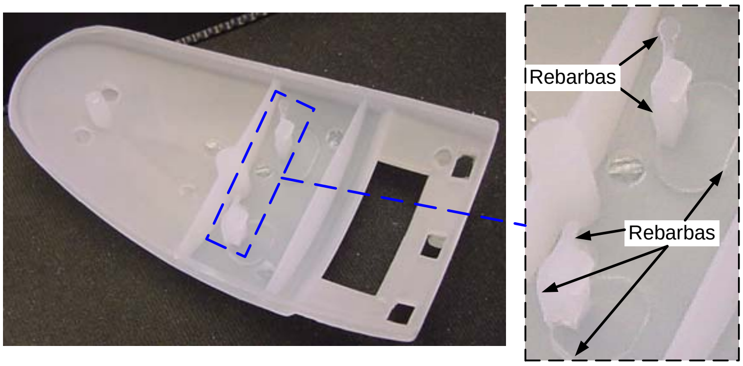


Figure 15. Injected prototypes and detail of the flashes

In relation to the gap observed due to excessive material removal during sanding, it is possible to say that the origin of this problem is in the CAD step, when the dimension of the small inserts and their respective beds are defined as the same (zero allowance). This problem can be dealt with by choosing an adequate offset value during the CAM step. The CAM systems usually allow using negative offset values in the model surfaces. Using this approach in the guide regions of the small inserts, it is possible to obtain the right allowance according to the required application (fixed or removable insert). This can eliminate or, at least, minimize the manual post processing stage. However, some specific research is required in order to identify the correct offset values, taking into account some variable such as: the machine, the tool length and diameter, the insert material, etc.

The flashes due to the gaps do not prevent the molding to be extracted, neither the removable inserts to work properly. Although they should be avoided, one should bare in mind that the injected part is a prototype and the flashes can be removed manually later. Notwithstanding, if the correct offset can be obtained and applied to the CAM stage, it is possible to say that these flashes will be reduced considerably.

6. CONCLUSIONS

The proposed systematic approach to overcome milling problems proved to be useful. The table summarizing the milling problems can help the user to identify the problems and some solutions have been proposed to some problems.

The solution proposed in both case studies were adequate to overcome the milling problems detected, however, other solutions can be thought, depend on the user experience. It can be stated that the systematic can be improved as the users gain more experience with it. The tables presented can be updated and improved once new problems are found or solutions are tested successfully.

Based on the analysis of the functionality of the prototype, it is possible to decide not to solve all the machining problems detected. As the case studies showed, the clip head was left with rounded laterals and some materials left in some corners were not considered relevant. These assumptions also require knowledge of the part function and can greatly simplify the insert manufacturing process. As a general rule, the lower the number of small inserts the better, because the final mold inserts are easier and quicker to be obtained.

The idea to manufacture all small inserts altogether proved to be successful, allowing speeding up their manufacture. The disposition of the small inserts will depend on the details to be milled and should be done in order to reduce the amount of resin used.

The allowance values of 0,02mm for the fixed small insert and 0,05mm for the removable small insert worked fine during injection. This is a good result, but some more research in this area should be carried out. The manual post processing of the small inserts was the critical step of the procedure. It requires a skillful user and can take a quite a long time. Therefore, some specific studies should be carried out in order to identify the offset to be applied in the CAM stage, which can eliminate or minimize the manual post processing step.

Although it has only been tested for polymeric resin, it is possible to infer that the small insert options can be applied to other metallic materials, such as aluminum, avoiding the time consuming EDM process in the prototype tooling manufacturing.

Some points in the proposed systematic can be improved and need to be studied. For instance, the minimum size of the small inserts recommended, the maximum number of small inserts that can be handle appropriately, etc. Some new researches in this area that are under development in NUFER/UTFPR will help to clarify some of these issues.

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9. RESPONSIBILITY NOTICE

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