PRODUCTION OF METALLIC TOOLS BY CERAMIC MOULDING – A RAPID TOOLING PROCESS

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Abstract

The conversion of rapid prototyping models into metallic tools for plastics injection using a ceramic moulding process is presented. The process main steps used in this experimental work were: production of the model (by rapid prototyping or conventional techniques), conversion into a silicone mould, production of a ceramic mould by casting a ceramic slurry that suffers a sol-gel reaction into a box, casting an alloy and finishing. Processing parameters like preheating of the ceramic moulds, pouring temperature and heat-treating of the moulds have a very important influence on the final characteristics of the metallic tools. This work presents the influence of the above parameters on the surface roughness, mechanical strength, dimensional changes, microstructure and capacity of details reproduction of the metallic tools.

Introduction

The aim of rapid tooling systems is to anticipate the overall development and production process of new products to the early project stages, in order to reduce the time to market and to avoid often very expensive design changes in advanced stages of the product development. The intention is to get the prototype in the same material and manufacturing process of the production parts. It is noticeable that rapid prototyping technologies allows to produce parts of any geometry and complexity and so, it can exhibit potential to compete with traditional CNC machining that, at present, dominates the wide tool manufacturing market. Another advantage is the possibility to get, directly embedded in the mould, conformal cooling lines that allow reducing injection-moulding cycle times.

The great interest for these technologies has been revealed in numerous projects that are being developed all over the industrial countries (United States, Europe and Asia), in universities, laboratories and companies whose policy, sometimes, is not trading, but to get strategic advantages over their competition [1].

We have developed a process to convert models obtained from RP techniques such as SL (stereolitography), LOM (laminated object manufacturing) or traditional model manufacturing techniques (silicone or resin reproduction), into metallic tools. The aim of this process is to produce working tools by directly pouring different types of metals (aluminium, copper, zinc or other alloys) into precision ceramic moulds. These tools may be used to obtain prototypes or pre-series through different manufacturing processes such as plastics injection, sheet metal forming, die casting, etc..

As an indirect rapid tooling process, and even as a production tooling, the production of metallic tools in Cu-Be or other alloys, by ceramic moulding can be much more promising than direct rapid tooling processes such as SLSm from DTM and DMLS from EOS.

The ceramic moulding is a precision casting process for the production of accurate castings with excellent surface finish and metallurgical integrity [2, 3]. Moulds are produced using refractory aggregates bonded with silica provided by a liquid ethyl silicate binder and are submitted to a high temperature firing treatment to produce an inert mould. The main advantages of this process are: dimensional stability, collapsibility and high resistance to thermal shock.

Ethyl silicate is a stable substance with no binding characteristics. Hydrolysis with water gives rise to monomers of silicic acid, which then polymerise in the form of an adhesive silica gel ($SiO_2.2H_2O$), bonding the refractory aggregates.

Ethyl silicate and water are immiscible, unless a mutual solvent such as ethyl alcohol is employed. This alcohol also serves to dilute the solution to the desired silica content. Hydrolysis may be carried out under either acid or alkaline conditions. However, alkaline conditions usually promote a fairly rapid gelation and consequently an acid hydrolysis is preferred (HCl).

Different ways for promoting the gelation of an acid hydrolysed ethyl silicate can be used, however the principle of pH control seems to be the most usual method. Hydrolysed ethyl silicate solutions are usually prepared at pH values between 1.5 and 3.0. These solutions are relatively stable in this pH range and also for pH values above 7.0. Adding adequate amounts of an alkaline agent (ammonia or ammonia salts) to an acid solution increases the pH value to approximately 5.0, the binder becomes unstable and the sol-gel reaction speeds up. The gelation time depends on the amount of gelling agent (gelation catalyst) and room temperature [4 - 6].

Many refractory materials such as zircon, alumina and aluminosilicates can be used in association with hydrolysed ethyl silicate to produce a slurry. These ceramic materials exhibit thermal and chemical stability, avoiding interaction with molten metals. The surface finish of cast tools can be improved if the refractory has a suitable particle size distribution. Careful selection of the raw materials granulometric distribution results in two particular advantages: the fine grains of the ceramics provide a smooth surface finish on the resultant casting, and the selection of a thermally stable refractory material ensures that the mould is not subject to unpredictable dimensional changes during the pre-heating and during the contact with the molten metal, thus enabling an accurate estimate of casting shrinkage [2, 3, 7]. The secret of successful ceramic mould production lies in the material mix specification and slurry preparation. It is essential to balance the grades of refractory material with the volume of binder and the amount of gelling agent, in order to produce high quality moulds [3].

After mixing all the components (ceramic aggregate + binder + catalyst), the liquid slurry is poured into the moulding box around the pattern. Within a short period of time, controlled by the amount of gelling agent, the mould material gels to a rubbery consistency and the pattern can be separated from the mould. Following, the mould is immediately torched (stabilization) to remove alcohol and to stop the sol-gel reaction. Torching produces a very fine crazed network in the surface and inside the ceramic mould, which does not affect the casting surface, since there is no metal penetration into the fine cracks, but may improve permeability to allow the escape of air/gases during casting. The moulds are then sintered in a furnace at a temperature around 1000 ºC, which ensures the elimination of combustible materials and a strong, rigid, inert, accurate and stable ceramic mould is produced. Upon heating, the silicic acid or silica gel from the binder condenses to form refractory silica cement, which provides the high strength developed during sintering [2, 8 - 10]. The two half moulds are produced by the same way and then they are joined to support the pouring of the metal.

After pouring a Cu-Be alloy and demoulding, the mechanical properties of the metallic tool can be improved by a heat treatment (solubilization and/or ageing), by the metastable precipitation of the non-equilibrium phases (age hardening mechanism) [11].

Experimental Work

In previous work [8, 9, 12] the best ceramic mixture and processing parameters to obtain ceramic moulds with suitable properties to support the pouring of Cu-Be alloys (with 2,8% Be and 0,8% Co) were established (table 1).

Table 1 - Processing parameters used to obtain the ceramic moulds [12].

Mixture Composition	60 wt% Zirconium Silicate, 30 wt% Aluminosilicates and 10 wt% Rutile
Binder	Hydrolysed Ethyl Silicate (Wacker TES 40)
Proportion Binder/Ceramic Aggregate [kg]	1 / 7.5
Mixture Time [s]/ Mixture Velocity [rpm]	180 / 1850
Gelation catalyst (Gelling agent)	Ammonia Hydroxide (2.5 wt%)
Stabilisation	Ignition immediately after demoulding
Sintering conditions	2 h at 1050 ºC

Fig. 1 A presents the model that has different leather textures, a proof quality coin and a high quality plastic airplane engine. Fig. 1 also shows the silicone mould (B) and the respective ceramic mould (D), obtained by pouring a ceramic slurry into the moulding box (C).

Processing parameters like pouring conditions (preheating of the ceramic mould and pouring temperature of the metal) have a very important influence on the final quality of the metallic tools. In this work, the effect of these parameters on the dimensional changes, surface roughness and microstructure are studied. The influence of the heat treatment conditions on mechanical strength of the metallic tools was also studied.

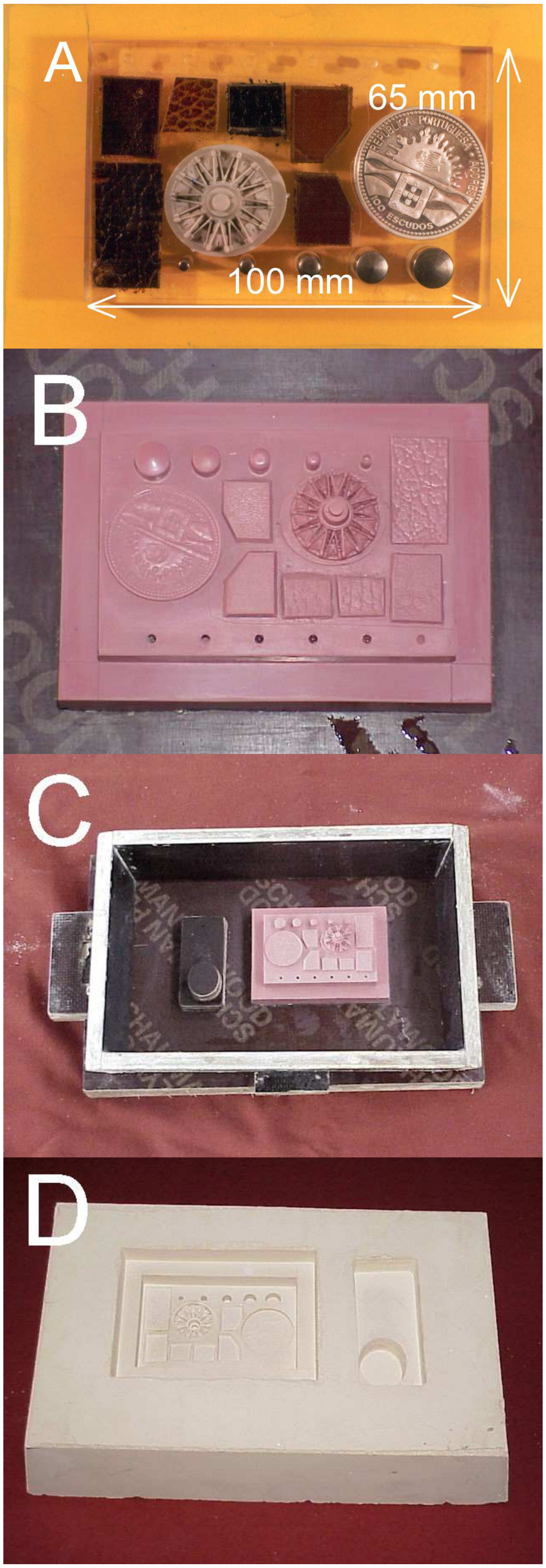

Fig. 1. Model (A), Silicone mould (B), pouring box (C) and ceramic mould (D), used to obtain metallic tools, with different pouring conditions.

Results and Discussion

One of the metallic tools obtained by pouring a Cu-Be alloy into the ceramic mould of fig. 1 – D is shown in fig. 2.

Fig. 2. Metallic tool obtained by pouring a Cu-Be alloy into a ceramic mould.

As one can see all the details of the model shown in fig. 1 - A are reproduced, with high quality. Fig. 3 shows the capacity of fine details reproduction obtained with this rapid tooling process, such as the one found in a proof quality coin.

Fig. 3. Reproduction, in a Cu-Be alloy, of a proof quality coin.

The results of the linear dimensional changes with pouring conditions (pre heating of the ceramic moulds and pouring temperature), measured into the metallic tools, are presented in fig. 4.

Although the good accuracy of the process the dimensional variation from the model to the metallic tool is sensible to the pouring parameters. In theory, the conditions that give the lowest contraction must be the lower pouring temperature and the higher pre heating temperature, which are not in accordance with the results presented in fig. 4.

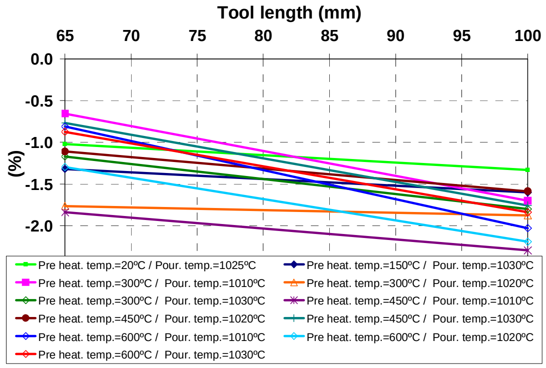

Fig. 4. Dimensional changes (in mm) as a function of the metallic tool length, for different preheating and pouring temperatures.

These results present some dispersion problems. However, the mean value for the contraction from 65 to 100 mm is around 1.5%. This value includes the dimensional changes from the model to the silicone, from the silicone to the ceramic mould and from this to the metallic tool. One must highlight that this value is less than the contraction of the Cu-Be alloys, cast in sand moulds that is around 1.7% [11], which is a great advantage of the process. The lowest contraction corresponds to the following conditions: pre heating of the ceramic mould at 300 ºC and Cu-Be alloy pouring temperature at 1010 ºC.

Actually it is possible to say that some of this large dispersion in these results is due to manual demoulding. Recent experiments with mechanical demoulding have shown that this dispersion is significantly reduced.

Prototypes surface quality has a great influence on the surface finish of the ceramic moulds. The difference between the surface roughness of the pattern and that of the final mould depends on the pouring temperature, pre heating of the ceramic mould and granulometric distribution of the refractory [2, 8, 12].

The roughness value of the ceramic moulds obtained with the processing conditions described in table 1, were around 1.2 μm. The roughness values of the corresponding regions measured in the metallic tools obtained with different pouring conditions are indicated in fig. 5.

There is no significant roughness variation (all the values of Ra are around 1.5μm) when the pouring or pre heating temperatures are varied.

Although the roughness of the metallic moulds has no dependency on the processing parameters like pre heating of the ceramic mould and pouring temperature, low pre heating and low pouring temperatures produces finer grains and brighter surfaces. However, some details are not completely reproduced.

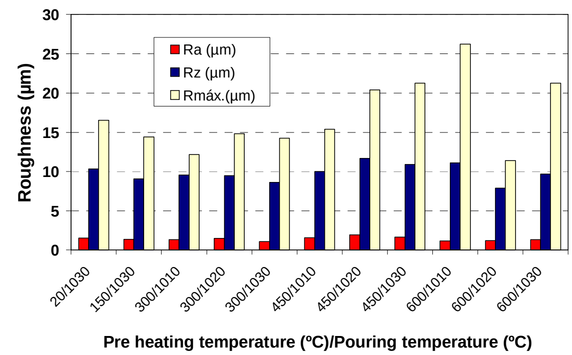

Fig. 5. Roughness variation of the metallic tools as a function of the ceramic mould temperature (pre heating) and the pouring temperature of a Cu-Be alloy (2.8% Be).

The microscopic evaluation of Cu-Be samples from the metallic tools, obtained with the different pouring parameters, does not show significant differences. The representative microstructure of this cast alloy is presented in fig. 6.

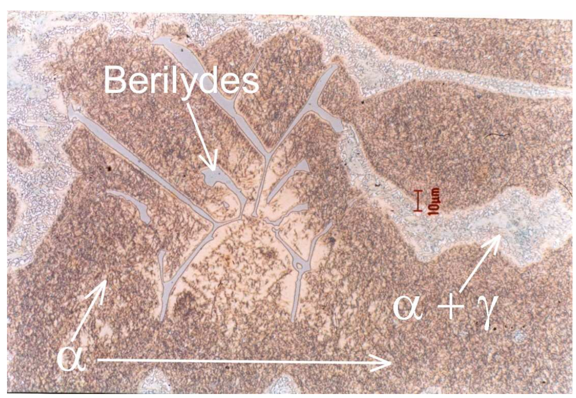

Fig. 6. Microstructure of a Cu-Be alloy (with 2.8% Be), indicating the different phases present in the alloy.

The influence of the heat treatment conditions in the hardness of the metallic tools is presented in fig. 7.

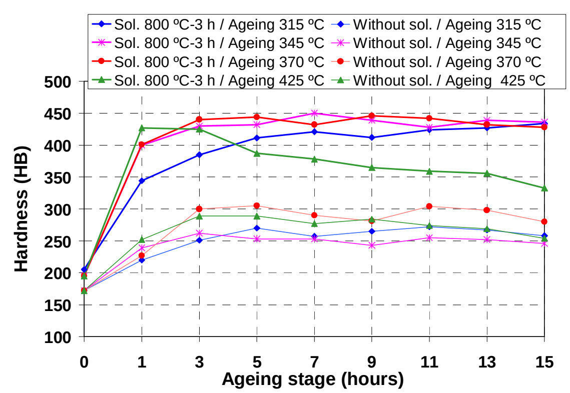

Fig. 7. Hardness with different heat treatment conditions.

As one can see in fig. 7, heat treatment of solubilization and ageing increases the hardness from values around 180 – 200 HB (after pouring) to values around 450 HB (solubilization at 800 ºC, during 3 h and ageing at 345 to 370 ºC during 7 – 9 h). In practice this heat treatment is very important because the life of the tool is improved.

In bibliography [11] it is frequently suggested a heat treatment of ageing without solubilization. In fact, fig. 7 shows that the improvement in mechanical properties obtained with this heat treatment (from 180 to 300 HB) is not so high as the one above described. Otherwise, the lower mechanical properties obtained with this heat treatment are enough for some applications.

The tools already obtained were used to produce 100 to 500 plastic prototypes for the automotive industry.

Conclusions

The ceramic moulding process is included in the indirect rapid tooling processes. This process has the capacity to quickly produce metallic tools for prototype production, with accurate reproduction of fine details.

Using adequate casting parameters (preheating temperature of the ceramic mould and the pouring temperature of the alloy) it is possible to obtain metallic tools with controlled dimensions variation. These parameters do not significantly affect the final surface roughness and the microstructure of the metallic tool.

The metallic tools can be used directly in prototypes production. However, the mechanical properties of tool (Cu-Be) can be optimised if an adequate age hardening treatment is used, namely solubilization at 800 ºC for 3 hours and ageing in the range 345-370 ºC for 7-9 hours.

Keywords

Rapid tooling, ceramic moulding, rapid prototyping, metallic tools, indirect conversion processes.

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