Validation of product and process design
by the use of a new rapid tooling process

François Pérès¹, Arthur Mofakhami²

CREATE : Rapid Prototyping Center
Laboratoire Productique Logistique
Ecole Centrale de Paris
Grande Voie des Vignes
92295 Châtenay-Malabry cedex
FRANCE

¹ Telephone: 1-41-13-14-52  Fax: 1-41-13-12-72  E-mail: peres@pl.ecp.fr
² Telephone: 1-41-13-15-67  Fax: 1-41-13-12-72  E-mail: mofakh@pl.ecp.fr

ABSTRACT

We propose in the paper a process, based on the use of a high velocity, electric arc metal spray thoroughly atomized on a master model in order to make a shell. The mold is realized by placing the sprayed alloy into a frame and reinforcing it with appropriate material. The first part of the paper presents briefly the main rapid prototyping and tooling techniques used in industry. We then describe the tool/moldmaking method which is a process to reproduce shapes very accurately. Given any model, a metal shell can be build up around it to desired thickness. We describe and comment the tasks leading to the shell making. The realization of the mold itself is also presented. In most cases, the spray alloy shell must be reinforced with backup. We expose the application fields of this new technique especially in term of product and process validation. We focus on the natural links with stereolithography. By comparison with conventional processes, we show how fabrication time and costs are dramatically reduced by integration of this new moldmaking method. Finally, we present the limits of the technique and the perspective of work and further research.

Keywords : design validation, product development, rapid prototyping and tooling, stereolithography
INTRODUCTION

Today in industry, the need to adapt the products to the market becomes vital. This adaptation will require to be able to satisfy conflicting parameters such as time, cost and quality. To achieve this almost unreachable goal, companies must review the way they organized the conception but also the production or industrialization departments. Furthermore, these changes must take place in a context where the market is often unstable and the investment capacity is most of the time reduced to its maximum. The fast evolution of techniques, needs or even fashions implies to always wonder: “does the product or service I propose fit the market expectations?” and “do I make it properly?”. These answers depend essentially on technical and temporal criteria, both of them being translated into an economical point of view by the company.

Time so appears as a primordial factor. Consequently, creativity must be followed by an ability to react with a time of response sufficiently short to be one of the winning arguments when proposing the product. Time to market is a key element in the companies success. The conventional development chain of a product requires the realization of sequential activities, linked together in a logical preestablished order. This serial way tends to disappear and is progressively substituted in many industries by a concurrent engineering approach which consists in placing the tasks in a parallel configuration to compare very early in the product development cycle, the objectives and expectations of the whole technical staff who contribute to the product making.

The unique goal of this approach is, as soon as possible, to validate the parameters intervening in the definition, realization and exploitation of the product. This validation will be easier if we can refer to physical models of the product and tooling required to its realization.

Rapid prototyping techniques allow to elaborate these physical models in a very short time. Validations made from prototypes implying the whole project team enable to quickly visualize the errors and limit their consequences (time or part losses for example). Therefore, rapid prototyping is helpful in order to validate:

✔ The product:
  • Conceptual validation
  • Esthetical, geometrical or dimensional validation
  • Functional validation
  • Mechanical, thermal or any physical solicitation validation
  • Finished machining validation

✔ The realization mode:
  • Tooling validation
  • Process validation
  • Fabrication cadence validation
In this context, rapid prototyping can be considered as a source of profit and used to:

- Improve reactivity with respect to market fluctuations
- Help creativity and development of new concepts in design
- Simplify communication between customer and supplier
- Optimize the integration of the product in its environment
- Anticipate fabrication, maintenance, control or conditioning problems
- Make rapid tests on the product to verify some of its characteristics (ergonomic, aerodynamic, …)
- …

So far, a large amount of research has been done on prototype making. Due to these investigations, various techniques and machines have been developed as we will see later on.

If research is still made on prototyping methods, more and more studies deal with rapid tooling which is an extension of prototyping concepts. In fact, classical prototyping techniques are usually not sufficient to deliver a model identical to the final product which only allows to validate the whole characteristics required in its making and use. The objective is then to make tooling which will help to realize prototypes in a way that will enable to validate not only the industrialized product but also its elaboration mode. First section of this paper will remain briefly the techniques used or being developed in terms of rapid prototyping and tooling.

In the second section, we will expose a rapid tooling technique based on the metallisation of a resin pattern in order to make a mold and used to get thermoplastics prototypes through injection. We will describe the tasks leading to the realization of the shell and the mold itself. The advantages of this method will be discussed. We will outline the limits of the technique and will comment the costs and delays resulting of such a process.

In the last section, we will eventually emphasize the future research made on the ground of rapid tooling.

1. RAPID TOOLING FROM PROTOTYPES

1.1 Rapid prototyping

In this sub-section we will shortly remind the historical development of rapid prototyping methods and will describe the principles of the most common techniques. For more details we suggest the reader to refer to reference [Bernard, Taillandier (1998)].
Stereolithography [Allanic & al (1992)], [Jacobs (1992)], [Nakagawa, Wei (1994)]: This method can be considered as the first real rapid prototyping technique. Developed in 1986 the method is now widely used all over the world.

Because the rapid tooling technique we are going to present in the next section is based on the use of a prototype made of resin after a stereolithography process, we will focus on its principles.

As for the other rapid prototyping processes, stereolithography requires that the part to be created is numerically defined and cut in thin parallel sections. This slicing process is made directly onto the computer at the end of the phase of design. In the last decade, most of the CAD programs currently used in industry have integrated this format in their basic module. Under action of a laser, a photosensitive liquid resin is solidified by a chemical transformation. The beam of light emitted by the laser is conducted on the resin surface by a set of dynamic mirrors. The move of these mirrors will make the light runs on the resin surface along the trajectory corresponding to the considered section. In its wake, the laser polymerizes the resin and only the exact section remains solidified. Precision, state of the surface and particularly manufacturing time depend on layer thickness selected. After realization of a section, the platform supporting the object being made goes down into the resin at a depth dependent on layer thickness (usually from 0.07 mm to 0.75 mm). Stacking-up of layers leads to a 3 dimensional part. Following polymerization of a section, a scraper is used to spread out the resin uniformly on the surface. Once resin level is steady-state, laser can start the next section. On figure 1 a photo and a sketch representing the principles of our stereolithography machine are presented.

Solid Ground Curing [Bertsch & al (1997)]: is another method based on resin polymerization. Unlike stereolithography, the process does not use a laser but a powerful ultra violet lamp coupled with a masking device. With this method, all points of a same section are simultaneously solidified. The mask, which is a negative of the section, is a glass plate covered on appropriate zones with a black electrostatic toner as in photocopier machines (ionography).
Selective Laser Sintering [EosSint (1996)], [Tas (1996)]: requires a thermal laser used to fuse a powder material mixed with a binder. On laser wake, powder is heated slightly above its melting point and agglomerate when cooling. A thermal treatment can be useful to improve physical properties of the part and reduce porosity. Prototype materials used depend on the powder, usually made from plastic, sand, ceramic or metal components.

3D Printing [Sachs & al (1996)]: is very similar to the previous technique. Its principle is based on powder agglomeration through deposition of binding droplets on the section points. When finished, the part is larger than it should be in order to compensate for the important shrinkage due to sintering. Here again, a thermal treatment will be required. 3D printing is sometimes used in ceramic molds making (Cf. § 1.2).

Fused Deposition Modeling [Merz & al (1994)]: which has been developed in 1988 uses a head mounted on a 3 axes CNC machine to deposite a fused thread on the part being made. Solidification is instantaneous when bringing the thread into contact with the previous section. Thread materials used are wax, nylon, polypropylene, ABS,… This process is quite fast and cheap and can be helpful to make empty parts.

Laminated Object Manufacturing [Gabriel (1997)]: does not use material change of state. Sheets are cut out, piled up and stuck. Cutting out can, according to the techniques, be the last operation. A thin sheet of paper covered by a polypropylene film is deposed on the previous section and pressed under temperature. Heat makes the film melt which sticks the paper sheet. A laser cuts out the outline of the considered section at a depth corresponding to the thickness of the sheet. The final part is very similar to wood.

Stratoconception [Barlier (1991)], [Barlier (1995)]: is a process very simple to implement. Actually, it does not need specific machines. Various sections are cut out in a plate through techniques such as water cutting, laser cutting or even milling. Assembly is realized by sticking, fusion or locating. In order to save up materials, an optimization is done to select the most adapted cutting plan. Almost all solid materials can be used in stratoconception. Moreover, as conventional machines are sufficient, large 3 Dimensional prototypes can be made.

The techniques presented so far are all based on matter adding. They are the most common methods used to realize, in a brief period, complex prototypes. Let us just mention here that an other way to make prototypes consists in removing matter. Techniques such as high speed machining or hot thread cutting are also widely used in industry [Cetim (1994)], [Essox (1996)], [Marchand (1992)].

1.2 Rapid Tooling

Up to now, the techniques we have exposed are most of the time unable to make prototypes in the same material than will be the final product. This is not a problem when controlling characteristics such as geometry, volume, aspect or parameters like aptitude to be machined or accessibility and modularity for maintenance but very often prototyping operations are required to validate other properties of the product. Most of the time, features like mechanical or thermal resistance, ability
to be integrated in a given context and to be assembled or faculty to run properly in a nominal mode of use must be checked before industrialization and serial tooling realization.

Rapid tooling techniques allow to make prototypes that will make those validations easier i.e. in a material identical to the final product or very similar on the ground of the characteristics to be controlled. Furthermore, rapid tooling is very useful when several parts must be tested to carry out the validation process (when using destructive control for instance). As we will see hereafter, most of rapid tooling techniques enable to realize a number of products superior to unity. Finally, beyond the product validation, the serial realization mode requires to be controlled to verify its capacity to deliver conform products in term of quality and rate as prescribed in the specifications. Some rapid tooling methods make this form of validation possible.

In this subsection we will talk about the main rapid tooling techniques used in industry to check the product process parameters early in the product development cycle. When thought and realized correctly, substantial savings can be expected from these validations. In the overview, we will start with rapid tooling concerned with plastic part realization before describing techniques used to make metallic products. More precision will be found in [Cabrera, Shellabear (1996)].

- **Silicon molding method** [Deschamps (1996)], [Ellis (1995)], [RPR (1993)]: is a well-known technique widely used in industry. The pattern which can be in any solid material (wood, metal, plastic, resin, …) is placed with casting canals in a box which is filled with liquid silicon until the part is totally covered. The box is then placed under vacuum conditions in order to evacuate gas bubbles likely to remain in the mold. Solidification by polymerization of the silicon requires 2 hours when placed in an oven, 24 hours when left outside in ambient temperature. The mold is then cut before being reconstituted once the pattern is extracted. In the place left free inside the silicon mold, it is then proceeded to vacuum casting of two mixed resins already degassed. The mold placed in an oven allows the part inside to solidify. When polymerization is over, the new part is removed and its casting canal cut. The mold can be then reused to make other parts. Prototypes are usually made of polyurethane plastics very similar to injected ABS or epoxy. Because of silicon fluidity, reproduction is very good. According to the complexity of the part until several hundreds of units can be made with a single mold. Parts can be rigid or flexible, opaque or transparent and even colored. The process is cheap and fast but the prototype made is not in the definitive product material.

- **RapidTool Process** [Dormal (1996)], [McAlea & al (1996)], [Tass & al (1996)]: has been developed to allow realization of direct metallic tooling for plastic injection. The process consists first to sinter the polymer binder contained in the metallic powder in order to link the metallic particles to form the part. This part, very fragile, is then placed in a polymer binder bath to improve its resistance by reducing inner porosity and space. Solidification is obtained by putting the part under medium temperature conditions. The last operation is the replacement of binder by copper. In an oven, temperature is first risen to the melting point of the binder which dissipates. Under high temperature, copper placed in block all around the part fuses and infiltrates the spaces. At the end of the process, the part is approximately composed of 50% of copper and 50% of steel. The metal obtained is similar to an aluminium in term of behavior. Up to several thousands of plastic parts can be injected but shrinkage due to sintering is not well controlled yet.
Direct Shell Production Casting [Sachs & al (1996)]: is derived from 3D printing technique used in rapid prototyping. The method can also be used in rapid tooling for metal casting as we said in the previous subsection (reader can refer to § 1.1 for a more complete description). A ceramic shell is made in which metal is cast.

Sand or Plaster Casting [Kalpakjian (1985)]: is one of the oldest manufacturing processes. The originality of the technique is that the pattern used to make the two halves of the mold is directly obtained from rapid prototyping techniques that confers to the process a substantial speed. As for silicon molding method, patterns may be made of wood, plaster, plastic, metal, resin, ..., depending on the size, shape, dimensional accuracy and quantity of castings required. The greater the number of castings desired, the stronger and more durable the material should be which will require to select the adequate prototyping method. Patterns are coated with a parting agent to facilitate their removal after the molds are made. After the two halves of the mold have been shaped, they are closed, clamped and weighted down to prevent separation of the mold sections when the metal is poured into the mold cavity.

Lost-wax, resin or paper models [Gabriel (1994)], [Gabriel (1996)]: is an old and commonly used casting process (also known as the investment casting). Once again, appropriate prototyping methods are suitable to accelerate the process through the use of a model made from stereolithography or laminated object manufacturing technique. The prototype can be duplicated in wax by sand casting or silicon molding method as described earlier. The wax model is then dipped into a refractory material. Once this initial coating is dried, it is recoated repeatedly to increase thickness. The mold sections are then dried in air and heated to temperature of 90 to 150°C in an inverted position to melt out the wax. The mold is then fired to 650 to 1050°C, depending on the metal to be cast, to drive off the water of crystallization. After the metal is poured and the casting has solidified, the mold is broken-up and the casting is removed. A number of patterns can be joined to make one mold, called a tree, thus increasing production rate.

2. THE COOL SPRAY MOLD MAKING METHOD

In this second part, we will show the principles of the cool spray mold making method. Dedicated to plastic parts obtained by injection this method utilizes a spray metal deposition system [Yeung & al (1995)]. The objective is the development of a low cost process for functional prototypes or pre-serial molding. This process allows the testing of design before a final tooling commitment, obviously very costly, is made. We will first describe step by step the shell making before focusing on the realization of the mold itself. We will eventually comment the application fields, the advantages as well as the limits of the technique.

2.1 Mold making

Further information can be found in [MCP (1995)], [MCP (1995)]. A flat aluminium plate, providing a reference plane can be used for mounting of the model (figure 2). Pattern and surface plate are coated with a fine spray of a dry release agent (fluorocarbon). Then, two or three thin coats of a polyvinyl alcohol are spread out to make the demolding of the pattern easier. The model to be sprayed must be isolated from the plate by the way of aluminium shims placed beneath the model and plaster forced under the edge. If needed, holes formed in post molding operations must be plugged using high temperature wax or any suitable material.
According to the overall size previously measured, a two layers aluminium frame is cut, placed and centered around the model to provide support and stiffness to the spray metal shell (figure 3). The frame is separated about 30 mm from the model. In order to get a better adhesion of the sprayed alloy, surfaces of the frame facing the pattern are sanded. Assembly of the frame requires first to proceed to drilling operations all around the finished tool surface at regular intervals. The distance between two consecutive holes is dependent on the frame size and must be consequently adapted. The frame is assembled by placing a bolt in its four corners and, for security reasons, one bolt in each direction away from the corners.

Prior to spraying, a reference point is selected to measure the model height. The objective is to control the thickness of the metal deposition. The first metal coating is made of a thin layer (about half a millimeter) of a tin/zinc alloy (figure 4). Once this first operation is over, the tin/zinc wire is removed and replaced with a 100% wire for the last spraying operation. The second metal coating is about one and a half mm thick. The total thickness should not exceed 2 mm which otherwise might cause cracks in corner zones.
The frame, the shell and the model are removed from the surface plate by breaking the plaster joint. The model is left in the shell as a protection of the molding surface during the next step of tool making. The cavity shell is positioned with the sprayed side of the shell up (figure 5). Aluminium bars are placed and bolted above the frame to make a rectangular cavity which will contain the back-up material. In some cases, copper tubing can be placed on the shell surface. The network will be used to heat or cool the tool by steam, hot oil or cool water circulation. A cloth must then be placed on the copper tubing fitting the shape of the inside cavity. To ensure a maximum coverage, the cloth can be split in several meshes reinforcing particularly the corner areas likely to be the sensitive points of the shell.

![Figure 5: Adding heating element cloth and building cavity](image)

Heat resistant and transmitting epoxy resin is then mixed with little aluminium spheres and poured onto the pipe and wire networks (figure 6). The resin is blended with epoxy curing agent and mixed with pellets in the proportion of one third of the mixture made of resin for two thirds composed of aluminium. The reinforced resin is worked around the copper tubing to fill the voids likely to weaken the sprayed shell. A rectangular and plane cloth can be placed at the upper surface for additional stiffness and covered again by back up material until 2 mm from the top of the outside bars. The frame is then left at room temperature during approximately 40 hours to make the epoxy resin solidify. The spray metal tool is then heated for 15 hours to definitely stabilize the resin.

![Figure 6: Blended mixture pouring](image)

Once the above operations have been carried out successfully, the procedure must be repeated to build up the other half of the mold. The pattern used in the first part of the process, remains in the sprayed shell. The patterns free-side facing up will be cleaned and all plaster or any foreign matter removed (figure 7). Cavity and model are then sprayed with a release agent
and parting films as previously. A second frame, made of two aluminium layers is cut and counter bored to match the first one. The implementation of heating device and cloth is similar to the first die respective operations. A heat resistant and transmitting epoxy resin reinforced as we showed earlier with aluminium pellets is poured. It is then proceeded to the solidification of the second die followed by the same heating sequence than the one completed on the initial half of the mold.

![Figure 7: Repeating operation for the second face of the pattern](image)

Both halves of the mold are disjointed with wedges driven between the upper and downer frames. The pattern, remained in the second die, is removed (figure 8). Both shells are cleaned. An additional die set is used to achieve completely the tooling and maintain both shells steady-state, one with respect to the other. The second half of the mold is centered on the corresponding die set element which has guide pin bushings. In order to eliminate completely voids between the die set and the tool, the squared volume, 2 millimeters high, left empty at the top of the die containing the shell is filled with an iron powder material instead of the aluminium spheres used so far. The die set is then positioned on the mold and strongly bolted. After having reconstituted the mold and returned it, the other half of the mold is filled with the same iron powder before being located and assembled as previously with the corresponding element of the die set. Mold surfaces are cleaned and polished thereby completing the realization of the tooling.

![Figure 8: Removing the pattern and closing the mold](image)

### 2.2 Equipment and products

Mold making requires the use of specific materials. We will not prescribe here specified products which are fully dependent on the geometric shape, matter, number and quality of prototypes to be made. We will just focus on the intrinsic properties expected for each product and will describe the hardware needed to proceed to the shell realization.
Wire: must have a melting point temperature sufficiently low to prevent irreversible damages to the pattern but high enough to resist to the injection temperature. Significant superficial hardness is needed to support injection pressure. In case of further shell operations wire material must accept machining. Low material shrinkage will ensure a good output quality. Other parameters such as ability to reproduce surfaces, bonding resistance, thermal dilatation, spraying aptitude or covering capability will have also to be considered.

Back-up resin: has to be characterized by a low thermal dilatation coefficient and a good capacity to put up with thermal shocks. Resin properties like compression and shear resistance, temperature endurance, viscosity, cure time and shrinkage will have to be carefully thought about. Occasionally, resin can be substituted with other backing solutions using laminating system such as fiberglass, kevlar or graphite or also low melt castable alloy.

Spray equipment unit: consists of a power pack, a control unit with twin-wire holders and a spraying gun. The power-pack produces a high arc current from a transformer close-coupled to a silicon diode rectifier assembly. The control unit has air regulators and pressure gauges necessary for controlling the flow of air to the wire feed motor and to the atomizing jet. The spray pistol has an air driven wire feed mechanism and an air nozzle assembly which forms the spray stream of metal as it melts and atomizes within the arc. Two copper tubes guide the wires to the arc zone in front of the nozzle. Metal spray gun can melt and spray any material including nickel, copper, stainless, zinc, aluminium and various alloys. Two wires are required to produce an arc.

Operator protection: is recommended to guarantee a good security level. It is advised that spraying be confined to an enclosed, highly ventilated area. The pattern and the surface plate should be placed in an enclosed spray cabin equipped with an exhaust fan to reduce fumes in the working zone. Operators should wear an air pressurized hood to minimize inhaling the oxide fumes produced during the spray operations.

2.3 Mold exploitation

The spray metal tooling though very different in its realization of a production mold can be used in a similar way. The major difference is the limit in the pressure injection as we will see in the next section. Once the tool is installed in the press it is heated to proper temperature (cool or hot according to the molding characteristics). In order to prevent damaging of the shell, precautions must be taken during the molding operations. A typical cycle of the cool spray moldmaking method required to extend tool life at its maximum can be as followed:

- Slow closure to avoid rapid flowing of the injected material under high pressure which would cause tool erosion.
- Sufficient cure time to ensure a complete cured part.
- Temperatures of the mold halves calculated to reduce by-pass clearance between them.
- Molding pressure determined and controlled to prevent high pressure damage to the tool during initial start-up.
- Application of a mold release coat, polishing, wiping and compressed air blowing to remove external matter in order to clean the tool surface after each molding cycle.
An example of mold and parts made from the cool spray mold making method is presented on figure 9.

Figure 9: Examples of realization

2.4 Method results and comments

A statistical analysis has been performed [PSA (1994)] which reveals that manufacturing cost of a metal sprayed mold stands for 45% of the total value of tooling realization. The other cost components are pattern forming (32%), equipment and material supplying (18%), design (4%) and final control (1%).

The cool spray mold making method is very convenient for flat shaped forms. The low compression resistance of the shell prevents the realization of prototypes made of viscous thermoplastic or parts made in mold with long flowing course of matter requiring elevated pressure injection. Some problems can also appear when ribs are numerous and the complexity of the part implies several partition lines. It must be mentioned as well that due to lack of accessibility, narrow and deep concave shapes are obviously quite difficult to spray. In such cases, aluminium blocks can be machined and inserted in the mold.

Beyond injection temperature and pressure, tooling life is dependent on parameters such as chemical composition and charge of the injected matter which may aggress the sprayed shell. Thermal shocks caused by disrupted injection campaigns are likely to damage the mold and consequently accelerate its death. Progressive temperature change or continuous injection would eliminate the problem. In such conditions, minimum tooling capacity is around 200 parts for uncharged thermoplastics (ABS, polypropylene,…) and 50 parts when incorporating charges like talc or fiberglass.
Once the mold is made, it cannot be modified directly. External blocks of metal can sometimes be added to the areas to be adjusted. When necessary, a second mold can be built up. The corresponding cost is reduced up to 30 percent since numerical definition and pattern can be reused.

Product and process validation levels are mainly dependent on injection parameters and mode.

Dimensional product can be fully validated. In metal sprayed molds, low injection pressure prevents a normal compactness as the one achieved in high pressure conditions. Consequently, mechanical characteristics and shock resistance of the injected prototype may differ from the serial product, limiting thus possibilities of validation. The difference is obviously as much attenuated as the mold prototype and injection mode are close to the serial process. Product aspect validation is possible and improved by prototype aptitude to be painted.

When pressure injection does not exceed 50 bars, the process can be regarded as representative. Beyond this value, process validation will be more speculative. In particular, precautions will have to be taken before concluding about mold thermal behavior and injected matter rheology which can be very distinct in the serial process. For low viscosity material, prototype deformation will be validated if number and position of injection entries and copper tubing network are identical in the serial mold design. Provided the latest conditions are verified, mold shrinkage validation will be also fulfilled. Prototype production rhythm (2 to 3 parts per hour) however will never match the serial rate which is scarcely expected from a prototype tooling.

3. **PROSPECTS**

3.1 **Technological evolution of the cool spray mold making method**

Studies are being made to ensure a better prototype realization, closer to the serial process. The objective is to improve the validation level remaining incomplete. Two ways must be simultaneously investigated.

The first one concerns the back up material which must be amended in order to guarantee firstly, a larger mold compression resistance to prevent collapsing risks, secondly, a better thermal behavior to allow higher temperatures inside the mold. Investigations are being carried out to use inorganic material to reinforce the sprayed shell. The better thermal and mechanical characteristics allowed already to inject 300 parts (car bumpers) in 3 injection campaigns and under pressure reaching 420 bars.

The second one deals with shell stiffness that has to be ameliorated. The aimed goals are increased erosion resistance in order to ensure injection of charged thermoplastics and improvement of tooling capability to amplify the number of prototypes elaborated from a single mold. Research is currently made about new sprayed materials and shell treatment by electrodeposition techniques.
3.2 Spray formed steel tooling

The process is designed to produce steel prototypes and production tooling in a fraction of the time needed to make tooling conventionally [MCP (1997)]. This is accomplished by spray molten metal directly onto a low cost accurate refractory pattern. These production tools are intended to produce an excess of one million components if required.

The starting point for the process is the same as for the manufacture of all tooling: the CAD file or a prototype component from which a CAD file can be created. Steel is sprayed onto a set of refractory pattern. The next step is then to produce a model of the tooling to be sprayed. As in the cool spray mold making method, the models are adjusted dimensionally to compensate for the small differences that may arise during the various processes due to thermal contraction and expansion of materials. Calculation is easy and CAD files modified accordingly.

The models of the tooling are then used to produce the refractory patterns required for the metal spray process. The process used is known as freeze casting. A slurry made of fine silica particles mixed in water is poured onto the model and vibrated to remove trapped air bubbles. It is then frozen solid. The freezing process gives rise to an irreversible gelation of the silica which turns into a solid refractory material. No loss in dimensional accuracy nor distortion arising from residual stresses are observed. The only dimensional changes that occur are the normal isotropic changes that arise due to the coefficient of thermal contraction of the model as it freezes and to the coefficient of thermal expansion of the refractory itself as it warms back to room temperature.

The refractory pattern is then removed from the model still frozen. The same model can be used over and over again to produce many identical copies of the refractory patterns. This makes it very easy and very cheap to produce duplicate refractories and therefore duplicate sets of tooling. Changes can also be made on the model to produce modified refractory patterns. This is extremely useful for rapid prototyping and temporary tooling manufacture.

The refractories are dried and pre-heated to the spray temperature prior to spraying. They are then sprayed according a process providing uniform coverage and control of the temperature which metal is deposited. Once an approximate 1 cm thickness shell is completed, the spray process must be interrupted to incorporate water cooling channels. Led section is molded to the required shape of the tubing network. The led is formed to a predetermined pattern taking account of the mold design and keeping the water cooling lines away from the areas where post spray machining will be required later. Led lines are then bedded down onto the surface. The spray process is then completed by depositing more metal directly over the led until sufficient thickness has been laid down to get the tool all the strength it will need in service. When this spray process is completed, the led is melted out to provide smooth water cooling channels.

This process which is being developed should allow to deliver a press ready serial mold in a time cut by a factor of 4 with respect to the conventional machining techniques. The key features of this spray process are firstly the ability to spray steel...
thick deposit in the conditions that allow proper control of the stresses and thus eliminate all of the distortions that would normally occur; secondly, the aptitude to lay water cooling channels as an integral part of the process. The channels can be curved and positioned where they are the most effective which leads to substantially reduce cycle times on the press. Cycle time reductions of 30 percent should be quite easily achieved.

The technique allows to work with high melting point alloys and is therefore well adapted to serial mold making. However, the method remains very costly because of the complexity of the equipment required. Financial profit will depend on the geometry of the part to be made and the capacity to reduce dramatically the product time to market. In most cases conventional methods remain still cheaper.

CONCLUSION

The paper described briefly the main rapid prototyping and tooling methods. The domain is very large and only the most common techniques were presented. It seems that nowadays, the perspectives of rapid technology development are oriented toward machines design allowing to deliver directly in a quick time and at a low cost not only the geometric prototype but as well the tooling required to test product functionality. Stereolithography research is now concerned with post operations consisting in realization of tooling from resin prototypes. Other promising processes deal with direct realization of tools from metal, sand or ceramic.

The emphasis was placed on the so-called cool spray moldmaking method which turned out to be very successful for specific shaped parts. The main steps of the method were exposed. Equipment and material necessary to perform the spray operations were also presented. Eventually, prototype realization was introduced and results discussed. The method proved to be particularly efficient in prototype validation but less suitable to validate high injection pressure processes.

Finally, prospective research has been exposed and, in particular, a new prototype tooling technique based on spray molten steel directly deposited onto a refractory pattern. The technique is very efficient but remains limited.

Although simulation methods are every day improved, physical prototypes are still required. Unlike mathematical algorithms, they are not influenced by restrictive hypotheses and can be adapted to the real context of making and use. Research and development of rapid techniques must continue to provide the companies the reactivity they need to grow and prosper.
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