From CAD and RP to innovative manufacturing

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FROM CAD AND RP TO INNOVATIVE MANUFACTURING

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Abstract: From CAD and Virtual Prototyping, there are already available many Rapid Prototyping (RP) techniques to produce physical, hand hold able parts. A brief overview is presented of some important aspects regarding how to get a good 3D solid model, how to transfer it to RP machines and how to produce quickly a physical prototype. The RP models could be used for different downstream applications. The paper gives some alternative tooling routes, depending on some criteria, such as: volume production, material and complexity of the parts. The RP models could be used as master models for vacuum casting, metal spraying, investment casting and other innovative manufacturing techniques.

Keywords: rapid prototyping and tooling, innovative manufacturing, vacuum casting, metal spraying.

1. Introduction

The paper is designed to provide technical specialists with an overview of the connections between CAD, 3D modeling, Rapid Prototyping (RP), Rapid Tooling (RT) and Innovative manufacturing.

The theoretical and practical experience on RP & RT gained in the last 8 years at the Technical University of Cluj-Napoca (RO) has been combined with the very good experience on Industrial Design, 3D Modeling and Virtual Prototyping, from Loughborough University (England). As a result of a very good co-operation between specialists from these two universities, the paper starts from 3D modeling, RP and it tries to indicate some alternative innovative manufacturing techniques, where RP is heading to.

Rapid Prototyping is the name given to a host of related technologies that are used to fabricate physical objects directly from CAD data sources. These methods are unique in that they add and bound materials in layers, to form objects. Such systems are also known by the general names solid freeform fabrication and layered technologies. They offer advantages in many applications, as compared to classical subtractive fabrication methods such as milling turning, etc.

RP and RT are good solutions, mainly when it is about rapid product development, or about low volume manufacturing of complex parts. That is because there are no limits for the complexity of the parts produced by RP, no special tools are needed, the only necessary input is the CAD data, the time to market is a lot smaller and the costs are reasonable.

In the distant future, there is no doubt that computers will be used to automatically manufacture objects, products and systems of every description and kind with no limit to complexity. The inputs to these fabrication systems will simply be raw materials and CAD data. We'll be able to efficiently make complex things in small volumes without tooling and with material properties that we can only dream about now. This scenario is a long way off, but the very real foundation for that world exists today.

2. Virtual Prototyping

The objective of designing products is to meet the customer requirements. That's why the design will progress through a number of stages such as:
- Idea generation, as an inspirational thought or from an evolutionary process. The outcome would be a new concept aimed at meeting specific customer needs.
- Filter concepts, such as marketing filter, technical capability to manufacture the items, financial filters, etc.
- Preliminary design, when the concept is developed to a level sufficient to assess its capability of meeting the customer needs
- Design iteration, when the design is reviewed several times to ensure that the customer needs are met and that the solution is cost effective

- Final design, which should take into account design for manufacture aspects, in order to ensure that the design will have the ability to be produced.

A clear and effective communication is very important throughout the design process, in order to meet both the customer needs and the business objectives.

A number of virtual prototyping tools and techniques are available to designer, in order to improve the communication process. Some of these virtual prototyping techniques are: visualizations, animations, concept models, virtual reality, neural networks, finite element analysis, simulations, etc.

With the CAD model in the appropriate format, a rendering option could be selected within the CAD system. Adjusting such parameters as color, lighting, texture, material, transparency, luminescence, etc, the model will be transformed into a pictorial image. Depending on the capability of the CAD system, the model can generally be rotated and positioned on the screen, enabling all aspects of the design to be viewed and assessed visually.

The items on the set can be moved to form a "fly through" and hence create the animation. Components and assemblies can be assigned constraints e.g. degrees of movement, through which they can move, enabling an animation sequence to be produced.

Anyhow, virtual prototyping can never replace physical prototyping. Even when the purpose is to improve the product development communication, the physical models made by RP represent a first class communication tool.

3. Solid modeling for RP

3.1.   Geometrical modeling requirements
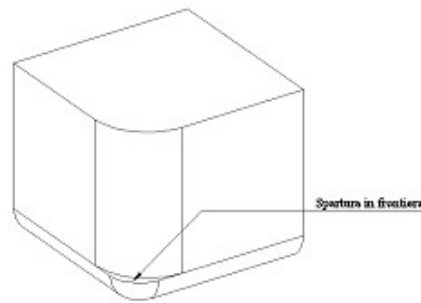
Fig. 1. A bad CAD model, due to a boundary break

If the virtual 3D model is not precise or if it is ambiguous, the 3D physical model made by RP will be a bad one, having errors, or being impossible to be made.

The designer needs to know some requirements for the 3D model, if that part is to be built in an automated manner by RP. The virtual 3D model needs to define a perfect closed object, which has a clear delimitation between its core and its external space. Not all the CAD systems are ensuring a proper 3D model for RP.

Fig. 2. A bad CAD model, due to a "flying surface"

Some examples of bad 3D models, which are not suitable for RP, are as follows:

- A frontier brake is illustrated in figure 1. In this case, it might happen that not all the profiles generated by the RP slicing software are closed.

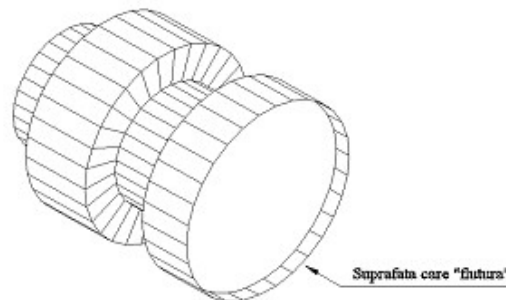- Other bad virtual model is illustrated in figure 2, where there are "flying surfaces", which are also leading to open planar curves, not suitable for RP machines.

- The Klein's torus illustrated in figure 3, is an example of a 3D model which apparently has no errors, but it does not represent a valid 3D object, because this entity does not split the space into two distinct regions. This entity is an example of a 3D model which does not represent the boundaries of a real object.
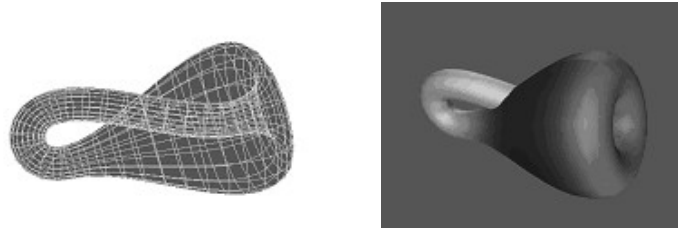

Fig. 3. The Klein's torus does not represent a real object's boundaries

Some of the best geometrical modelers are the CSG (Constructive Solid Geometry) and the BREP (Boundary REPresentation) modelers.

A CSG modeler represents an object by a collection of primitives (parallelepiped, pyramid, cylinder, cone, etc.), using operations between the primitives, such as union, intersection, subtraction, etc. The computer's memory works in this case with a binary tree, whose nodes are either the geometrical primitives, or different operations applied to the primitives. The advantage is that they always generate valid objects, but there are limits regarding the complexity of the parts.

A BREP modeler generates a model as a collection of surfaces which form the object's boundaries. They have the possibility to describe both simple surfaces (planar or rotational patches, translational or rotational sweeps, etc.) and complex surfaces (Bezier patches, B-Spline and NURBS surfaces, etc). In this case, the advantage is that a more complex body shape is generated, but it is not sure anymore that we get a valid, real object. The user needs to check if all the boundaries are perfectly closed. All the CAD systems (ProEngineer, CATIA, SolidWorks, etc.) combine these two modeling mechanisms and it is up to designer, how to choose a combined appropriate 3D modeling strategy, according to the shape's complexity of the part.

3.2. Transferring the CAD model to the RP machines

Different CAD models store a virtual 3D model in different ways. That is why a standard interface is necessary between the CAD systems and the RP machines.
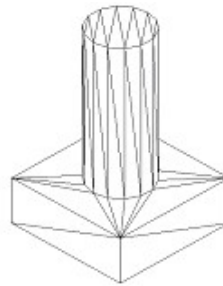
Fig. 4. The STL representation of a CAD model

The generally accepted interface to all the RP machines is the STL file format (patented by 3D Systems Inc.), which approximates the virtual model with a collection of planar triangles. In this way, there is a precise representation only for planar boundaries and all the curved ones will only be approximated in the STL representation. Figure 4 illustrates the STL representation of a simple model.

There are two types of STL files. The ASCII STL files are easier to be read, understood and modified, using an usual text editor, but their length is higher (they need bigger storage resources). The binary STL files are more compact.

Figure 5 presents the method used to describe every triangular facet, by:

- A set of (x, y, z) coordinates for all three triangle's points

- The Cartesian components of a unit vector which is perpendicular to the facet, pointing to the outer side of the object.

```
                                        z
                                        ↑              A (150, 50, 100)
                                        |              B (50, 150, 100)
                                     N̄  |  N̄           C (50, 50, 100)
                                     C  ↑  ↑           N̄ (0, 0, 1)
                                      \ | /
                                       \|/         B
                                    A
                                                        y

                               x
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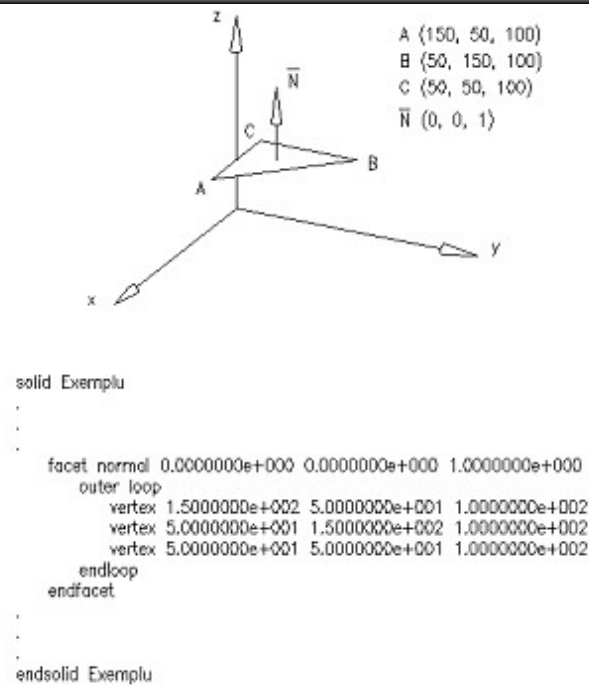
```
solid Exemplu
    .
    .
    .
    facet normal  0.0000000e+000  0.0000000e+000  1.0000000e+000
        outer loop
            vertex  1.5000000e+002  5.0000000e+001  1.0000000e+002
            vertex  5.0000000e+001  1.5000000e+002  1.0000000e+002
            vertex  5.0000000e+001  5.0000000e+001  1.0000000e+002
        endloop
    endfacet
    .
    .
    .
endsolid Exemplu
```

Fig. 5. A STL file's portion, corresponding to one triangular facet

All the CAD systems offer different parameters used to control the quality of the STL approximation, before saving a STL file, which could be transferred to any RP machine.

At present, none of the available RP machines can produce a part directly from a CAD model. Before a CAD representation can be turned into a physical part, some degree of pre-processing is required to get the model into a STL file format that the RP machines can read.

4. Rapid prototyping techniques

Rapid Prototyping (RP) is a modern technology which takes 3D CAD data and reproduces a physical model in a very short time, normally hours, without the need for any specific moulds or tooling. Instead, all the RP techniques build parts by continuously adding layers of material. This enables them to build very complex parts. There are many RP methods available today: Stereolithography (SLA), Laminated Object Manufacturing (LOM), Fused Deposition Modeling (FDM), Selective Laser Sintering (SLS), Laser Engineering Net Shaping (LENS) and others.

It is difficult to say, which one of the available RP methods is better, because each of them have both advantages and disadvantages. When selecting the appropriate RP method for a particular job, there are some aspects to be considered, such as:

- Shape complexity of the part;
- Required dimensional accuracy, surface roughness, mechanical properties;
- Purpose of using the RP model (e.g. check the design or functional role);
- Further tooling applications (e.g. vacuum casting, metal spraying, investment casting);
- Type of required material, etc.

4.1. The stereolithography process

Stereolithography is a process that produces 3D solid parts made from resins. A laser beam scans across the platform, where the polymer in a liquid state is in the tank. The machine has an optical scanning system, driven by the computer.

The laser beam solidifies the polymer in the point where it touches the resin surface. By contouring all the part profiles, a layer gets solidified.

The new solidified layer moves down into the liquid resin, together with the platform and comes back again, up to a lower altitude, according to the layer thickness. Then a leveling system adjusts the liquid surface and the laser starts scanning the next layer.
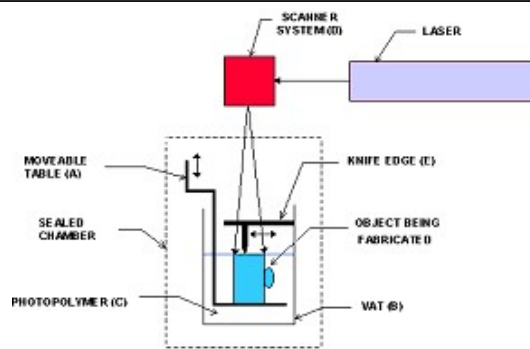
Fig. 6. Stereolithography

The main steps for manufacturing the SLA parts are as follows:

- ❑ CAD modeling;
- ❑ Prepare the virtual part;
- ❑ Set-up the SLA-250 machine;
- ❑ Finish the part and post-curing it.

Post-curing process takes place into an ultra-violet waves oven. It completes the solidification process of the remaining liquid volume of the part.

4.2. Laminated object manufacturing

The Laminated Object Manufacturing (LOM) is a new manufacturing method, where a 3D physical model is build by adding, bounding and cutting successive layers, within a cycle that repeats itself, beginning with the first layer from the part's base and ending with the last layer from part's top, using a machine such the one illustrated in figure 7.
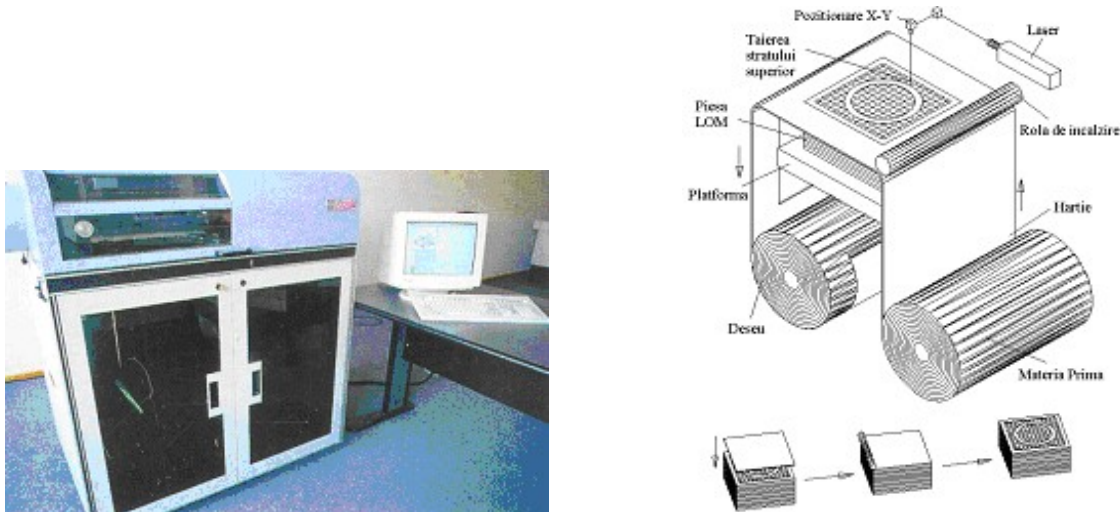

Fig. 7. Laminated object manufacturing, Technical University of Cluj-Napoca

This RP method starts from a *.STL file, which contains the virtual model of the part. This file is loaded into the LOMSlice software and it is sliced into thin layers. The thickness is equal with the thickness of the paper (0.1 mm approximately). The LOMSlice software calculates the profile of the part from every sliced layer. These profiles are going to be cut by burning, layer by layer. The laser beam starts cutting the inner/outer profile in every cross section of the part and then cuts a double hatch into the extra-material which is going to be removed when extracting the LOM model.

The platform moves down with 50-60 mm, the paper advances so that new paper comes on the top of the previous cut layer, the platform goes up and the heater moves across it, in order stuck the new layer aver the previous one, by worming up and pressing it.

The laser starts cutting the next layer and the building process ends when the height of the deposited layers reaches the z_{max} part's height.
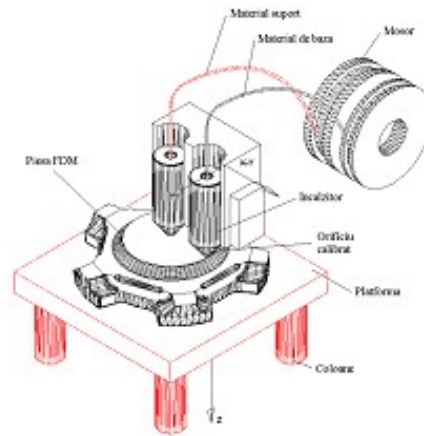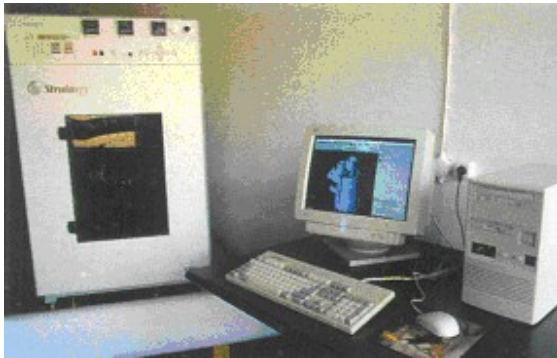
4.3. Fused deposition modeling

Fig. 8. Fused deposition modeling, Technical University of Cluj-Napoca

This rapid prototyping method is based on warming up the plastic material, until it almost reaches its melting point and extruding the semi-liquid plastic material, in order to be deposited, where the part shape requires. The key of this technique is the strict temperature control, that the material is warmed up and kept at, during the deposition process. The plastic material could be ABS plastic wire, or polyamide. The working temperature for the ABS plastic wire is 270 ˚C, when the material is into a semi-liquid state and can be extruded through a thin tip with a 0.254 or 0.127 mm diameter.

4.4. Selective laser sintering

The CO_2 laser beam is directed and focused by an optical system, in order to do the scanning of the first layer of the part. Once the profile in one layer is sintered, the working platform (component 6 from fig. 9) moves down with a layer thickness length. The pistons push up new powder material from the cartridges and the transportation roller takes the new powder and spreads it across the previous sintered layer. The next layers of the parts will be sintered and the process continues, until the last layer from the top of the part.
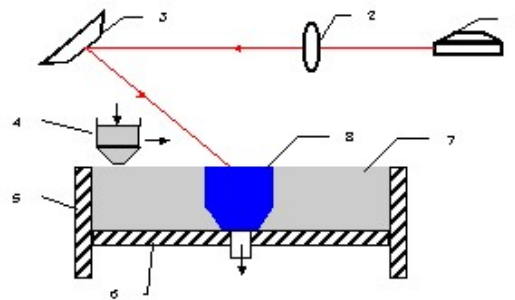

Fig. 9. Selective laser sintering, Technical University of Cluj-Napoca

The parts are embedded powder material at the end of the SLS process. They need to be extracted, cleaned up using a brush and the compressor / exhauster, for the fine details areas. This cleaning operation is important because if some powder remains inside a channel of the part, that powder gets solidified during post processing and cannot be removed later on, in case of metal powder SLS.

4.5. Laser engineering net shaping

Its strength lies in the ability to fabricate fully-dense metal parts with good metallurgical properties at reasonable speeds.

A high power laser is used to melt metal powder supplied coaxially to the focus of the laser beam through a deposition head (C). The laser beam typically travels through the centre of the head and is focused to a small spot by one or more lenses (B). The X-Y table (D) is moved in raster fashion to fabricate each layer of the object. Typically the head is moved up vertically as each layer is completed. The laser beam may be delivered to the work by any convenient means. A simple right angle mirror (E) is shown, but fiber optics could also be used. Metal powders (A) are delivered and

distributed around the circumference of the head either by gravity, or by using an inert, pressurized carrier gas (G). Even in cases where it's not required for feeding, an inert shroud gas (F) is typically used to shield the melt pool from atmospheric oxygen for better control of properties, and to promote layer to layer adhesion by providing better surface wetting.
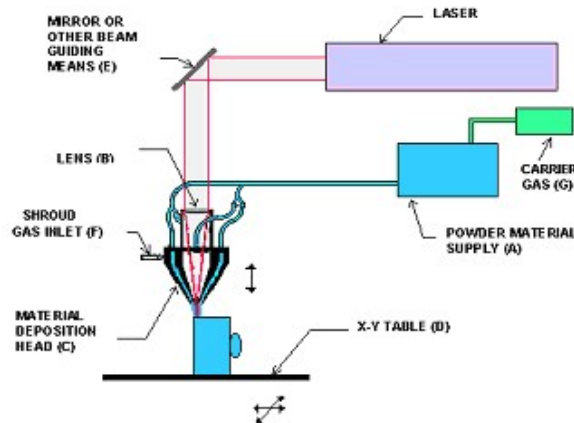

Fig. 10. Laser engineering net shaping

The building area is usually contained within a chamber both to isolate the process from the ambient surroundings and to shield the operators from possible exposure to fine powders and the laser beam. The laser power used varies greatly, from a few hundred watts to 20 KW or more, depending on the particular material, feed-rate and other parameters. Objects fabricated are near net shape, but generally will require finish machining. They are fully-dense with good grain structure, and have properties similar to, or even better than the intrinsic materials.

Initial applications are concentrated on the fabrication and repair of injection molding tools and the fabrication of large titanium and other exotic metal parts for aerospace applications. This emphasis is partly due to the fact that support structures for overhanging sections generated by the technology are fully dense and hard to remove. These applications don't need to address that problem. Work is ongoing to find a more convenient means of generating supports.

5. Rapid tooling and innovative manufacturing

Rapid Tooling (RT) is a generic term used to describe a range of manufacturing technologies associate with reducing time-to market. The applications for RT are diverse, encompasses a wide range of manufacturing sectors from plastic injection molding through to super-alloys for the aerospace and defense industries.

The principle of RT is to utilize both CAD data and Rapid Prototyping (RP) to produce patterns around which tooling cavities can be manufactured. With the exception of laminated tooling, RT techniques do not rely on material removal process such as milling, die sinking or wire erosion. Rather than removing material from a solid block, RT uses a variety of techniques to add material into the form of a cavity. RT cavities can be produced directly using RP processes such as stereolithography (SL), or Selective Laser Sintering (SLS). More commonly however, cavities are produced by replicating a RP master pattern using a secondary casting process. In each case, RT relies on the availability of either an accurate master pattern or CAD data suitable for driving RP technologies.

Rapid Tooling is also refereed to as soft tooling, low volume tooling, low cost tooling or reverse response tooling. In each case however, the principle is to reduce either lead times, tooling cost or in many cases, a combination of both. Given the consumer drive for more product variants at lower cost, rapid tooling is considered by many to be a prerequisite concurrent process used alongside conventional „hard tool" manufacture.

In summary Rapid Tooling provides a number of manufacturing business opportunities such as reduced time to market, tool design insurance, responsive tooling in the face of mass customization, low investment tooling for SME's and cost effective route for design iterations prior to high volume manufacturing.

5.1. Rapid tooling selection

Choosing isn't easy. The net result is that there are a bewildering number of routes to get to a final functional part or tool starting from a CAD definition. The choice depends on the application, volume of parts to be produced, final material and accuracy requirements, rapid prototyping process used, and numerous other factors. Choosing isn't easy since most technologies are immature, have significant limitations, and there are usually several competing alternatives.

Table 1 shows a selection alternatives for the manufacture of tooling to produce polymer based components. The important criteria are the production volume and the final part material.

Table 1. RT of the plastic parts

Plastic parts	Production material	Simulant
1 off	Not cost effective	Rapid Prototype part FDM – ABS SL – Epoxy resin SLS - Duraform
10 off	AIM tooling Ceramic cast tooling Sprayed metal tooling (Zinc)	Vacuum Casting Thin RIM moulding RP parts
100 off	AIM tooling Spray metal tooling (steel) Resin Cast Tooling Laser sintered tools	RIM moulding
1,000 parts	Cast kirksite tooling Laser sintered tools Cast aluminium tooling 3D - Keltool	Not cost effective
10,000 parts +	Laser sintered tooling Electroformed tooling Investment cast tools (steel) 3D - Keltool	Not cost effective

The key selection criteria is establishing the longevity of the tool surface for the given production material. The harder the tool-face, the longer the tool life. In addition to tool material, some indication of lead-time should also be considered when selecting a tooling route. The softer the tool material, the quicker the tool manufacture. For instance, soft silicon tools can be cast in a matter of hours; ceramic tools can be cast in a matter of days where as non-ferrous alloys and powder metallurgy tools take some weeks to prepare.

Table 2 shows the selection method for the manufacture of direct part and production tooling for ferrous and non-ferrous metals. The selection criteria are the production volume and the final part material.

Table 2. RT of the metal parts

Metal parts	Production material	Simulant
1 off	Investment cast from SLA, SLS, FDM Sand casting from RP patterns	Laser sintered metals
10 off	Investment cast from SLA, SLS, FDM Sand casting from RP patterns	Spin casting Laser sintered metals
100 off	Investment cast from waxes produced in RP cavities	Spin casting
1,000 parts	Die casting into Keltool Die casting into laminated tools	Not cost effective
10,000 parts +	Die casting into Keltool Die casting into laminated tools Investment cast steel dies	Not cost effective

5.2.   Vacuum casting – silicon rubber tooling

This is a standard method of making small quantities of polymer parts. Any rapid prototyping-generated part can be used as a pattern to make silicone rubber tooling. These tools can be used to mold small to medium quantities of parts in a large variety of urethane, epoxy or other polymers. Fig. 11 illustrates a pair of molds and the resin part, made by vacuum casting at the Technical University of Cluj-Napoca.

Fig. 11. Vacuum casting, Technical University of Cluj-Napoca

The process is carried out by placing the RP-generated pattern in a frame, usually made of wood. The pattern itself usually must undergo secondary operations to bring it to the desired state of accuracy and finish before it can be used. Silicone rubber room temperature vulcanizing (RTV) molding compound is then poured around the pattern. It may be necessary to apply a vacuum to the assembly to pull air bubbles out of the rubber and insure fidelity to the pattern. Once the rubber has solidified, the pattern is removed and the mold is ready to be used. Silicone rubber tooling is most often used in manual casting processes, but in recent years more automated technologies have appeared. So-called reaction injection molding (RIM) systems can produce several parts per hour from rubber molds. Molds also last longer because of the lower exposure time to chemical processes.

5.3.   Sprayed metal tooling

In this case, an epoxy or low melting temperature metal alloy tool is prepared by casting this material against an RP-generated pattern. A thin metal coating is then arc-sprayed on the resultant mould's working surface to give it greater strength. Tool life is about the same as for aluminum-filled epoxy, but the method can accommodate larger parts. Fig. 12 illustrates a pair of metal sprayed tools made at TUCN. These were backed up with enforced resins and used to produce plastic parts by injection molding, using the MCP 100 KSA machine. Different injection pressure has been used, to test which is the optimal pressure to be used, in order to protect these soft tools.

Fig. 12. Metal spraying, TUCN

Interest in the development of injection moulds by rapid prototyping technology has been very keen. Making injection moulds by subtractive CNC or spark erosion methods is extremely slow and expensive.

The general limitations of RP methods compared to CNC today are that they produce somewhat less accurate and less durable tools, may have part size and geometry limitations, don't necessarily produce identical parts to hardened tooling, and tools may not easily be modified or corrected using typical tool-making techniques. These limitations vary both as function of the specific RP technology used and for each individual case.

5.4.   Investment castings

These processes typically involve thickly coating, or investing, a pattern which is made of a material that melts or burns out easily with a material such as ceramic, which doesn't. The pattern may be extended to provide a gate into which metal in a hot, liquid state is poured. Passageways are also provided to allow melted or burned pattern material and air

to escape. The invested pattern is then fired in a furnace to burn out or melt the pattern and fuse the ceramic into a strong hollow mould. Molten metal is then poured into the ceramic mould.
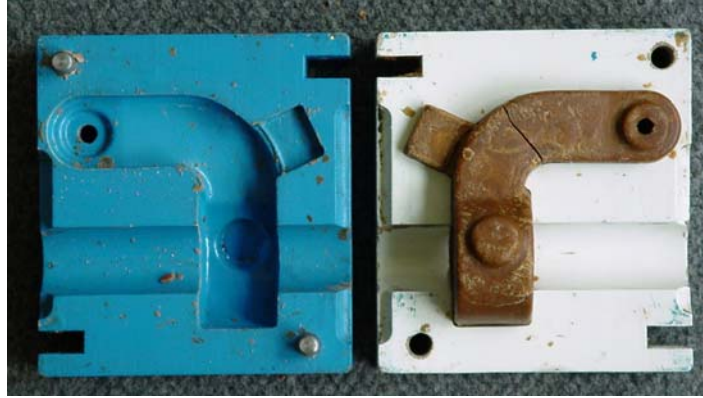

Fig. 13. Wax model produced in RP molds, at TUCN

After the metal cools and hardens, the mould is broken away to reveal the final object. Extra gate material is cut off and usually the part will require substantial finish machining and clean-up. Fig. 13 illustrates how the wax models (required by investment casting), were produced at TUCN, using moulds made by laminated object manufacturing.

6. Conclusions

Rapid Prototyping systems can't yet produce parts in a wide enough range of materials at a fast enough rate, to match the enormous spectrum of requirements of industry and science. Conventional processes such as molding and casting are still the only means available to do that, but RP is often the starting point for making these processes faster, cheaper and better.

The great majority of moulds today are still made using subtractive fabrication. Market acceptance for RP-based methods will continue to increase as business demands faster time to market, more individualized and shorter run products, and existing technical limitations are overcome.

Additive fabrication methods are not better than subtractive ones, nor will they become complete replacements for them. Milling, turning, EDM and other subtractive methods have reached an extraordinary level of development and they continue to evolve. They are fast, versatile, inexpensive, readily available and well-understood by large numbers of practitioners. Indeed, in many if not the majority of cases they are quite sufficient to make prototypes rapidly, and as yet have no equal when it's necessary to make very precise parts in final materials.

Engineering and manufacturing account for most of the use of rapid prototyping technology today. The main applications of rapid prototyping in engineering are: Concept Modeling, Functional Testing, Tooling and Manufacturing.

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